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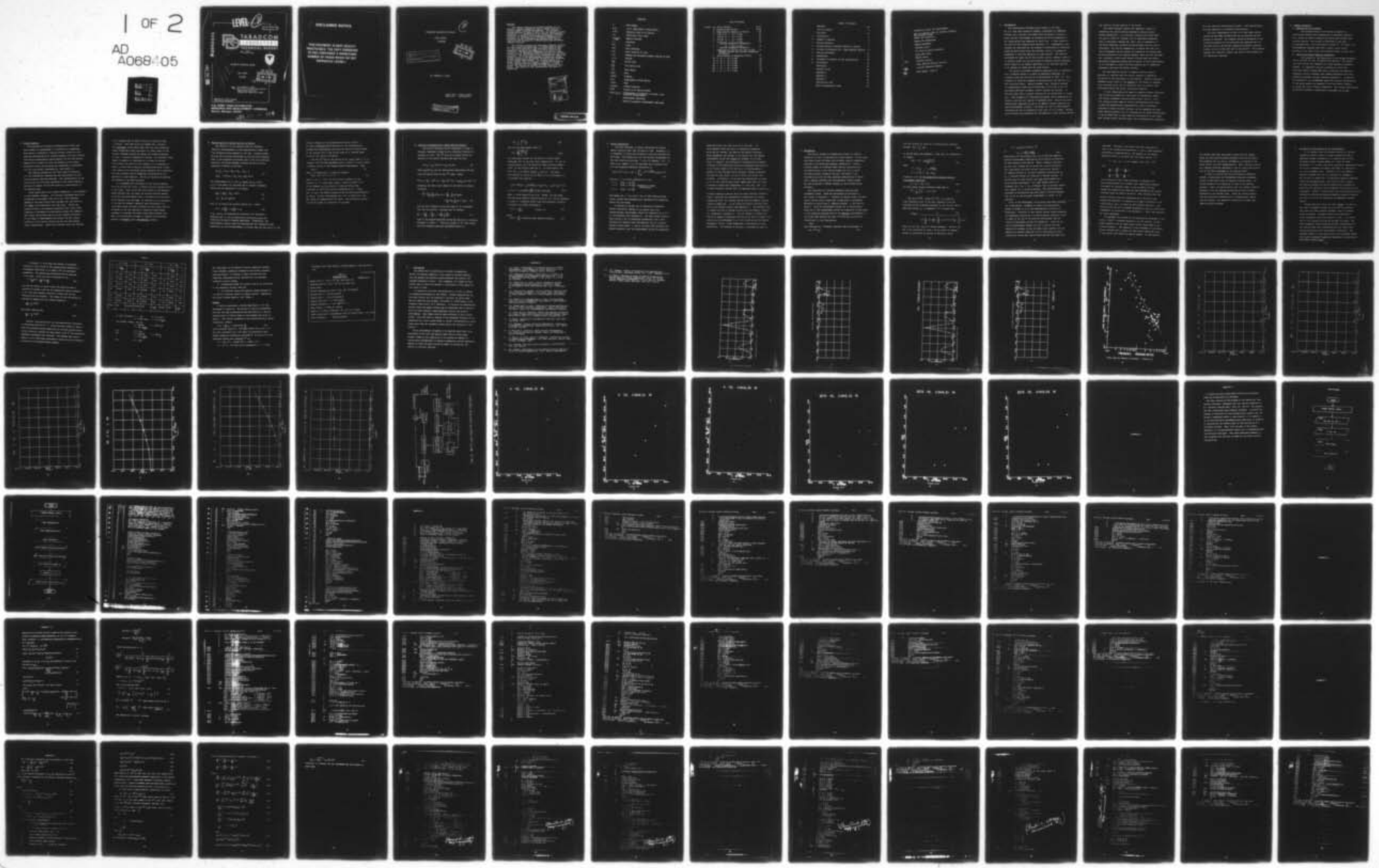

TARADCOM

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TECHNICAL REPORT

NO. 12377

AUTOMOTIVE SUSPENSION CONTROL

FINAL REPORT

Oct 1978

by Dr. Herbert K. Sachs

Wayne State University

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2

AUTOMOTIVE SUSPENSION CONTROLS

FINAL REPORT

Oct 1978

DR. HERBERT K. SACHS

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Abstract

This report contains the software package for an adaptive, optimal suspension control system relative to terrain random vibration disturbances. The proposed problem solution is shown to fall into two separate program categories: a) recognition of the terrain and parameter selection, by means of an on-board minicomputer or microprocessor, b) optimization of suspension parameters for arbitrary terrain configurations obtained from terrain statistics and executed on a centrally-located stationary computer facility.

The interface between the stationary computer facility and the on-board microprocessor is accomplished by means of a data bank prepared at the stationary facility and permanently stored in the memory of the on-board microprocessor. The suspension parameters are set by a servo-control unit on the vehicle which is activated by the microprocessor. The servo-control unit regulates the supply and release of air in the hydro-pneumatic suspension system, thereby increasing or decreasing the spring rate according to the optimal requirements. In a similar manner the damper orifice size is increased or diminished depending on the required effective damping parameter. If need arises, the vehicle can operate at fixed suspension parameters. The results of the investigation are shown in graph form.

NOTATION

a	Wave mumber
A(m)	P.S.D. amplitude of road profile
A(m^2)	Effective area of air spring
a,b	Subscripts, axle, body
c($\frac{N\text{-}sec}{m}$)	Damping constant
C_i	Constants
F(N)	Force
H(m)	Axle clearance
h(t)	Input function of time
h,h*	Complex and conjugate complex funcion of time
i,n,m	Indices
k($\frac{N}{m}$)	Spring rate
K($\frac{N}{m}$)	Tire spring rate
ℓ(m)	Wave length
m(kg)	Mass
p(N/m)	Pressure
s(m)	Displacement across spring
t(sec)	Time
u(m/sec)	Forward velocity
V(m^3)	Volume of air spring system
x_f(m),x_a,x_b	Displacement in direction of travel, also vibration displacements
X	Displacement amplitude
y	Relative vibration displacement amplitude

List of Figures

Table of Contents

α	Probability factor for displacement
γ	Ratio of specific heat at constant pressure and constant volume
δ	Symbol for variation.
Δ	Symbol for determinant
ζ	Damping parameter
η	Frequency ratio
μ	K/k ratio of spring constants
μ_1	m_a/m_b mass ratio
ρ	Weight factor
τ (sec)	Vibration period
ϕ	Power spectral density function
$\omega_i \frac{Rad}{Sec}$	Circular frequency Rad/Sec
$\Omega \frac{Rad}{Sec}$	Wave number, (also a)

1) Introduction

The investigation discussed herein began in 1975 when the U.S. Army Tank Automotive Command, predecessor to TARADCOM, entered into a contract with Wayne State University to pursue a study entitled "Development of Computerized Vehicle Suspensions". The investigation was completed in March 1976. A final report of the work was then submitted and approved, [1]. Subsequently a new proposal was submitted for the purpose of establishing a functional algorithm which would allow the automatic control of suspension parameters on vehicles operating in rough terrain. The vehicles considered are heavy and of the military variety; however, there is no inherent reason why the principles of adaptive control discussed herein should not be equally applicable to all vehicles required to be operable at speed over off-road terrain.

The notion of automatic suspension appeared first in connection with a complete design in a paper by Federspiel-Labrosse, [2]. A similar study was carried out by Westinghouse in 1965, [3]. The necessity of improving syspension characteristics was soon put on a more scientific basis. Works by Bender, Paul, Fenoglio, Karnopp (at Massachusetts Institute of Technology at the time [4,5,6,7]) considered feed-back automatic control systems for vehicles. It was next shown that a transfer function can be synthesized (n. Wiener [8]). Also Thompson [9] considered the optimal active suspension for bounce, pitch and roll control of passenger cars. None of the above publications suggested the use of an adaptive control employing on-board minicomputer circuits. The reason for this is that computer technology was not as advanced at that time, as it is today. Neither size nor price form obstacles for the adoption of such control methods

now, and will be much less so in the future.

The terms "optimal" control and "adaptive" control in connection with active vehicle suspension designs require further explanation. In a strictly literary sense there does not exist a "best" or "optimal" set of suspension parameters that is realizable, because the "best" type of suspension is one which completely isolates the sprung mass from any form of road shock. Any and all suspensions, no matter how soft, are force transducers and the softer the suspension the greater must be the excursions of the unsprung masses, which are not limitless. But, obviously, within given design criteria there are better performing suspension systems and the object of this investigation is to find means to select the best possible set of suspension parameters that meet the design criteria.

The term adaptive control is commonly used by control engineers to indicate that the control process is adapted to the source of the disturbance or perturbation. Another alternative feedback control where in the response of the system is compared with a desired output and the controller acts to minimize that difference between the actual and desired response.

In this investigation we employ an adaptive control algorithm that allows pre-sampling of the source of disturbance, namely the terrain roughness, from statistical data, [10,11]. From the infinitely wide range of terrain configurations that exist a large and substantially representative class of terrains, referred to herein as model terrains, can be assembled and their power spectral density (p.s.d.) functions can be placed side-by-side. It can be shown that in most cases the distribution of the roughness follows similar patterns which can be mathematically expressed

by error functions (discovered by Gauss). Such distributions are also referred to as Gaussian distributions.

For this investigation a total of 13 such model terrain statistics were made available and one was selected for the purpose of analysis. The computer algorithm dedicated to the on-board microprocessor was simulated and combined with the off-board terrain and optimal suspension parameter selection process, so as to close the look of the process. The following chapters will explain in detail the logic of the program and its operational features.

2) Summary of Results

a) Reconstruction of terrain.

The reconstruction of the terrain by means of a fast Fourier analysis and regeneration of measurable acceleration values at vehicle unsprung and sprung mass yielded very accurate results. The terrain as described in the form of tabulated data, [10] is plotted in Figure 19. Of course, the accelerometers employed must have a nearly linear output relative to the input within the frequency domain of their use.

b) Central Stationary Computer Simulations

The program for the computation of the Optimal parameter matrix has been written, documented and executed. The results have been plotted and compared with fixed suspension parameter systems. At comparable vertical acceleration levels the realizable speeds (speeds made good) of systems with adaptive suspension control exceeded those speeds, obtainable with fixed suspension parameter systems (passive suspension). If vehicles are operated at the recommended speeds the vertical accelerations of the sprung masses are expected to be sufficiently reduced to extend the life of vehicle components. But without statistically significant evidence no quantitative statement can be made.

3) Terrain Analysis

The signifiance of terrain configurations is that once their pattern is established it is possible to reconstruct them without a substantial loss of accuracy relative to the response characteristics of vehicles passing over such terrains. From terrain measurements (approximately 120 for each terrain sampled over a length of circa 120 meters) one can obtain equivalent Fourier series which are considered as representative for each terrain configuration. (see Figure 1).

The computer program for the "Fast Fourier Transform" [12] was successfully executed and the coefficients of each sine and cosine term were obtained. The reconstruction of the terrain from the 128 terms considered in the series showed an accuracy of between 97% and 99% relative to distribution of the measured data.

Since random data do not repeat themselves, it is necessary to take assembly averages. All terrains considered herein are considered to be ergodic, that is to say, that different samples of the same terrain when averaged over the length of the sample yield essentially the same value. Taking the squared values of the measured elevations from a mean level (squaring is necessary to avoid getting simply the algebraic mean value) and dividing the sum of all squared elevations by the number of measurements one obtains the mean square elevation of the terrain profile and the root mean square value, respectively. Hence for an ergodic input the averages

of all samples must be nearly alike for a specific type of terrain. Note that we do not assume that terrains are stationary, which would imply that the road elevations repeat themselves within multiples of a base length of the terrain, because terrains do change over longer distances. In fact, it would be necessary to collect an infinitely large number of samples to characterize all types of terrain. From a practical point of view, however, it is possible to select a finite set of terrain configurations which a particular vehicle will encounter during operation and to determine the most suitable form of suspension characteristics for operation in such terrains. The set of terrains so selected are referred to as model terrains.

It is assumed that the wheels of the vehicle passing over the terrain will stay in contact with the terrain profile at all times. Also, since the total length of the measured sample extends over 100 times the average distance between value sets the mean square value of elevation for each wheel may be assumed to be the same. In contrast to this assumption if one were to analyze a specific wave disturbance of a fixed wave length the wheel elevation of each wheel would be different at any one time and it therefore would become necessary to consider the phase relationship between each wheel (the distinction is made to indicate the difference between a stochastic and a deterministic input).

4) Reconstruction of Terrain Profile on Vehicle

The vehicle is to be equipped with low frequency sensitive accelerometers on the superstructure (body) and high frequency accelerometers on the axle (unsprung mass). With m_b the pro-rated sprung mass, m_a the pro-rated unsprung mass, k the suspension stiffness rate, K the tire stiffness rate and c the shock absorber constant we can write the equations of motion in the form

$$
\begin{aligned}
m_b \ddot{x}_b + k x_b + c\dot{x}_b - kx_a - c\dot{x}_a &= 0 \\
m_a \ddot{x}_a + (K+k)x_a + c\dot{x}_a - kx_b - c\dot{x}_b &= Kh(t)
\end{aligned} \qquad (1)
$$

The displacements in (1) are x_b (body) and x_a (axle). h(t) is the wheel lift and drop due to terrain roughness. Adding the two equations (1) we obtain

$$m_b\ddot{x}_b + m_a\ddot{x}_a + Kx_a = Kh(t) \qquad (2)$$

$$x_a = \int_{\tau'} \left(\int_{\tau} \ddot{x}_a dt\right)dt \qquad (3)$$

From (2) we obtain the terrain profile h(t), namely

$$h(t) = \ddot{x}_b\left(\frac{m_b}{K}\right) + \ddot{x}_a\left(\frac{m_a}{K}\right) + x_a \qquad (2a)$$

If $\ddot{x}_b$ and $\ddot{x}_a$ are measured and converted into electronic impulses then (3) can be obtained by integrating twice and inverting the sign on summing amplifiers. Alternately, the accelerometer outputs could be digitized and the integration done numerically on the microprocessor. In either case the the result of (2a)

yields a reading of the reconstructed terrain profile. In order to demonstrate the accuracy of the reconstruction process the investigators converted the spatial Fourier series of the terrain into a time series based on a constant speed motion of the vehicle as follows.

Let the n^{th} term of the series be sin (nax_f) where n is an integer, a is the wave parameter $(a=2\pi/\ell)$ where ℓ is wave length in meters) and x_f is the forward motion displacement. Then

$$x_f = u.t \tag{4}$$

where u is speed and t is time the argument

$$nax_f = n(2\pi\ u/\ell)\cdot t = n\cdot\omega\cdot t \tag{5}$$

where in (5) $\omega = 2\pi u/\ell$ is the circular frequency of the harmonic of "ℓ" meter wave length. Referring back to (1) we can compute $\ddot{x}_a$, $\ddot{x}_b$ relative to each and every term contained in the Fourier series representing h(t). These are, in fact, the signals sensed by the on-board accelerometers. $\ddot{x}_b$ and $\ddot{x}_a$ is then reintroduced into (2a) to obtain h(t) and the output is compared with the input. The correlation proved to be on the order of a fraction of a percent.

5) <u>Process of Averaging h(t), Power Spectral Density.</u>

The terrain elevation may be expressed in terms of discrete (measured) values or as a continous function of distance or time. The n^{th} term of a Fourier series expansion of the terrain function may have the form

$$h(t)_n = h_{nc} \cos n\omega t + h_{ns} \sin n\omega t \qquad (6)$$

where h_{nc} and h_{ns} are the coefficients associated with the sine and cosine terms of the n^{th} order. Hence

$$h^2(t)_n = h_{nc}^2 \cos^2 n\omega t + h_{ns}^2 \sin^2 n\omega t + h_{nc}h_{ns} \sin 2n\omega t \qquad (7)$$

Averaging the above with respect to one period of length τ we obtain

$$\bar{h}_n^2 = \frac{h_{nc}^2}{\tau} \int_\tau \cos^2 n\omega t \, dt + \frac{h_{ns}^2}{\tau} \int_\tau \sin^2 n\omega t dt$$

$$+ \frac{h_{nc}}{\tau} h_{ns} \int_\tau \sin 2 n\omega t dt \qquad (8)$$

Now the last integral on the left side of (8) integrated over the full period τ vanishes and (8) becomes

$$\bar{h}_n^2 = \left(\frac{h_{nc}^2}{2} + \frac{h_{ns}^2}{2}\right) = \left(\frac{h_{nc}^2 + h_{ns}^2}{2}\right) \qquad (9)$$

Each of the squared amplitude values $\bar{h}_n^2$ belongs to a discrete frequency of order n . Then, the average of all such values over the frequency spectrum considered herein is

$$\bar{h}^2 = \frac{1}{n} \sum_{1}^{120} \bar{h}_n^2 \tag{10}$$

and its root mean square value is

$$\bar{h}_n = \sqrt{\frac{1}{n} \sum_{1}^{120} \bar{h}_n^2} \tag{10a}$$

For each model terrain we can obtain its mean square amplitude (10) or its root (10a) respectively. If (10) is plotted versus $(n\omega)^2$ we obtain the power spectral density curve of the terrain (see Fig.1). In this Figure 1 we plot the $_{10}\log(\bar{h}^2/a)$ versus $_{10}\log(a)$. The dense distribution of points can be seen to lie in proximity of a straight line given by

$$_{10}\log(\bar{h}_1^2/a_1) - {_{10}\log}(\bar{h}_n^2/a_n) = ({_{10}\log} a_1 - {_{10}\log} a_n) f \tag{11}$$

$$\text{or } \log f = ({_{10}\log}[\bar{h}_1^2 a_n / \bar{h}_n^2 a_1]) / {_{10}\log}(a_1/a_n) \tag{11a}$$

where f is the slope of the line. Bender [13] has shown that the power spectral density function (11) can be expressed in terms of frequency rather than wave parameter yielding a straight line image expressed by

$$\phi(n\omega) = \frac{-\bar{h}u}{(n\omega)^2} \qquad \text{(Figure 1c)} \tag{12}$$

where

$$\phi(n\omega) = \frac{h_n^2}{2\omega} = \text{discrete power spectral density.} \tag{13}$$

6) Design Constraints

The axle clearance is usually determined by several design criteria other than softness of ride. Therefore, it is necessary to avoid the incidence of the axle striking the axle stops. The probability that the maximal displacement of the axle relative to the body Y will lie between $\pm \alpha\bar{y} = \pm H$ where α is a number, H is the available axle clearance and $\bar{y}$ is the expected suspension deflection, is

$$\text{Prob}\,[-\alpha\bar{y} \leq y(t) \leq \alpha\bar{y}] = \int_{-\alpha\bar{y}}^{\alpha\bar{y}} e^{(-(y/\bar{y})^2/2)}\, dy/\bar{y}(2\pi)^{1/2} \tag{14}$$

and for α = 1,2,3 this probability is [14]

$$\left.\begin{array}{ll} \alpha = 1 & \text{Prob.} = 68.3\% \\ \alpha = 2 & \text{Prob.} = 95.4\% \\ \alpha = 3 & \text{Prob.} = 99.7\% \end{array}\right] \text{— Gaussian or normal distribution}$$

This means for α = 3, in only 3 out of 1000 working cycles would Y exceed the allowable axle clearance H and therefore strike the axle stops.

In seeking an optimal set of suspension parameters, design constraints imposed on the system limit the average maximal displacement across the suspension $\bar{y}$ to $1/\alpha$ = 1/3 of available axle clearance H. For each terrain profile there exists a set of suspension parameters k and c that minimizes the maximal body accelerations $|\ddot{x}_b|$ at a certain average forward speed u and at the same time satisfies the design constraint that the displacement across the suspension

should be within the limit H 99.7% of the time. At other speeds,u,there are sets of suspension parameters which are not optimal, yet satisfy the design constraint. These parameters are optimal to the extent that the maximal displacement across the suspension elements is utilized. Since, in general, the acceleration transmissibility depends inversely on the deflection across the suspension and directly on the forward speed of the vehicle,it is advantageous to exhaust all the available axle clearance (without frequently striking the axle stops), so as to obtain the sofest ride possible. In Figures 2,3,4 we show the acceleration in units of "g" of the vehicle body versus "speed made good" for three differently chosen axle clearances H = .15m,.21m, .24m. All of these represent optimal data, as explained above, relative to

variable suspension spring rates and shock absorber constants. Figure 5 portrays the acceleration transmissibility versus "speed made good" for constant spring rate and damping constant (passive suspension). In all cases the results obtained refer only to one terrain profile (see Appendix 1). The formulas used to compute the set of optimal spring rates and damping constants are presented in Appendix 2. For the purpose of showing the effects of speed on suspension deflection we show in Figure 6 the relative axle displacement $\bar{y}$ vs. u for fixed spring and damping parameters. Figure 7 shows comparison of acceleration transmissibility. The meaning of the data is discussed on page 18.

7) Methodology

The control process is schematically shown in Figure 8 (Figure 22 of [1]) in the form of a block diagram. At the right hand lower corner are shown the off-board logistic operations executed on any stationary computer installation. Given a discrete number of different model terrain statistics and the descriptions of the vehicle masses and tire or track stiffness optimal parameter matrices (see Table 1) are obtained which give the best possible combinations of spring rates, damping constants and corresponding forward speeds. The data are placed in memory storage on the on-board micro-processor.

The computation of optimal parameters requires many programming steps. These are documented and attached to this report in Appendix 2. Speaking in general terms, the mean square terrain profile amplitude is amplified or attenuated depending on spring rate k, damping constant c, and forward speed u. Only two displacement values are of significance. These are a) the displacement across the suspension as mentioned in the foregoing paragraph and b) the absolute displacement of the sprung mass because the peak accelerations are directly proportional to that displacement.

Thus:

peak acceleration = frequency squared times displacement or

$$|a_c| = \omega^2 \cdot |x_b| \tag{14}$$

and (14) written in units of g (gravitational constant) becomes $|\bar{a}_c| = \frac{\omega^2}{g}\,|X_b|$ (14a)

It can be shown (see appendix 2) that $|X_b|$ is a function of $|Y|$ namely

$$|X_b| = |Y| \; \frac{(1+4\zeta^2\eta^2)^{1/2}}{\eta^2} \qquad (15)$$

where

$$\eta^2 = \omega^2/\omega_n^2 \cdot \zeta = c/2\sqrt{km_b}\ ;$$

$$\omega^2 = 4\pi^2u^2/\ell^2;\ \omega_n^2 = k/m_b\ .$$

Instead of Y we use <u>the permissible average relative displacement amplitude</u>

$$\bar{y} = H/\alpha = H/3.\,(\alpha=3) \qquad (16)$$

The mean square terrain elevation amplitude is:

$$\bar{h}^2 = \frac{1}{2m}\sum_{1}^{m} h_n^2 \ ; \ (m = 120). \qquad (17)$$

The ratio $\bar{y}^2/\bar{h}^2$, where $\bar{y}^2 = H^2/9$, is a specific number depending only on the axle clearance H and the measured terrain roughness expressed by the Fourier series amplitude values h_n. In appendix 2 it is shown that:

$$(\bar{y}^2/\bar{h}^2) = \frac{\eta^4}{[\eta^4 \frac{\omega_b^2}{\Omega_a^2} - \eta^2[1+\frac{k}{K} + \frac{\omega_b^2}{\Omega_a^2}]+1]^2 + \zeta^2\eta^2[\eta^2(\frac{k}{K} + \frac{\omega_b^2}{\Omega_a^2})-1]^2} \qquad (18)$$

where in (18) $\Omega_a^2 = K/m_a$ is a known parameter. Solving (18) for η^2 as a function of k and ζ we can infer the forward speeds u_i pertaining to the set of solutions, since

$$\omega^2 = 4\pi^2 u_i^2/\ell^2 = (k_i/m_b)\cdot\eta_i^2$$

or

$$u_i = \eta_i \ell \sqrt{k_i}/(2\pi\sqrt{m_b}) \qquad (19)$$

Substitution of the solution into (15) yields the absolute expected displacement amplitude $\bar{x}_b$ which should be minimized for best possible ride quality. Again, assuming ζ constant one can find a unique set of values for u and k satisfying this requirement and after further iteration by varying ζ (or damping constant c) the best parameter configuration u_o, k_o, c_o emerges whereby the subscript o denotes optimum. It follows that for each terrain only <u>one</u> forward speed will yield optimal performance. For other speeds there is a parameter set k (u), c (u), different from the optimal values, that renders (15) a relative minimum. The above described procedure of optimization has been coded in *Fortran* language and, as far as the principal investigator is aware, it is orginial.

Prior to the development of the above described procedure the investigators attempted to employ the optimization method of Bender et al of the *Massachusetts Institute of* Technology. According to that method optimal system responses are obtained by minimizing a so-called penalty function P which is equal to the sum of the absolute displacement and the relative displacement across the suspension. Since the relative displacements depend not only on spring rate and damping but foremost on the available axle clearance one can develop a so-called trade-off curve of acceleration transmissibility versus mean terrain amplitude and available axle

clearance. Obviously, the greater the axle clearance the less is the trasmitted acceleration, or for a fixed acceptable acceleration transmissibility, the greater is the vehicle speed with which it can move over the rough terrain. If

$$P = \rho \bar{x}_b + \alpha \bar{y} \ , \ (\rho \text{ is a number, } 10^{-4} < \rho < 10^{4}) \qquad (20)$$

then

$$\frac{dP}{dk} = \rho \frac{d\bar{x}_b}{dk} + \alpha \frac{d\bar{y}}{dk} = o$$
$$(21)$$
$$\frac{dP}{dc} = c \frac{d\bar{x}_b}{dc} + \alpha \frac{d\bar{y}}{dc} = o$$

yield values of k and c that minimize, or maximize (20). The differentiation (21) yields a very complicated algebraic polynomial of the eight power in the variables and even though the equations are coded for data processing the results obtained cannot be readily verified. They indicated that the penalty function could be represented by a relatively flat surface and therefore is insensitive to small variations in the coefficients k and c on which $\bar{x}_b$ and $\bar{y}$ depend implicity. The results yield one set of optimal parameters k_o and c_o, practically, independent of variations in the parameter c. Thus, this approach was later discarded.

To implement the results of the optimization developed in this study, a Table 1, prepared especially for the vehicle, is then placed together with the mean square terrain amplitudes in the on-board computer. The computer is also programed to reconstruct terrain profiles and to obtain the mean square amplitude value of the terrain over which the vehicle passes. It then selects

the nearest amplitude value model terrain and the nearest speed for which pre-calculated parameter sets are available. The parameter set (k_o and c_o) information is relayed to the servo control unit for implementation. Then, the servo control unit changes inflation pressures of the air spring and orifice size of the shock absorbers to the desired levels.

In order to execute the control function a comparison between instantaneous and recommended suspension parameter values is made based upon the measured forward speed. The optimal speed will be displaced in sight of the vehicle operator. Then, the servo-control unit will change inflation pressure of the air bellows springs and orifice of shock absorbers to the desired level. Since the terrain profile will be continually scanned within a predetermined length (say 100 meters), the operation constitutes a closed loop adaptive control process.

8) Discussion of the Results of the Investigation

It is apparent that the economic benefits of optimal suspension control reside in either extended periods of operation between overhauls, or in reduced time to cover distances (higher average speed) or in both of these advantages. It is also clear that performance improvements require an initial investment (no matter how small in relation to the total equipment cost). Whether or not the expected benefits outweigh the cost is a question of judgement. But the gain in speed over a conventional passive suspension system can be demonstrated. Let terrain profile, sprung and unsprung masses, tire spring rate and axle clearance be equal for two vehicles, one with passive and one with active suspension. Figure 7 clearly shows that the acceleration transmissibility through the passive suspension system is greater than that of the active suspension at comparable forward speeds.

Transmissibility ratios are never unique. By this we mean that bi-quadratic equations can yield two distinct real roots for each circular frequency value or forward speed considered. Frequency spectra have maxima at a finite frequency value and minimum at o and ∞. On either side of the frequency giving the maximum lie higher and lower frequency values yielding the same transmissibility. For reasons other than transmissibility one cannot make springs arbitrarily soft and dashpots ineffective. The parameter search is then restricted to the frequency domain that yields reasonable suspension parameters at practically realizable forward speeds.

In figures, 9, 10 we show the effects of parameter variation k and ζ, which is the dimensionless parameter of the damping coefficient c, on speed u for the optimized suspension. The spring force variations may be realized in two ways. Since the rate is defined as [15]

$$k = \frac{d}{ds}(pA) = \frac{dp}{ds}A + p\frac{dA}{ds} \tag{22}$$

one has the choice to alter either the effective area A relative to stroke s and let the pressure be nearly constant or to vary the pressure relative to stroke and let the effective area be constant. The former of the two choices is realized by shaping the air cushion requiring

$$\frac{dA}{ds} = \frac{k}{p} \quad (m^2/m) \tag{23}$$

The latter implies that

$$\frac{dp}{ds} = \frac{k}{A} \quad (N/m^3) \tag{24}$$

However, the spring rates are non-monotonially increasing or decreasing function of u giving the data listed in Table I. From the recorded forward speed and the recorded, reconstructed, terrain function yielding the mean square value $\bar{h}^2$ the appropriate suspension parameters are selected. The amended data matrix (Table 1) will yield body acceleration values which are relatively best for the recorded forward speeds.

Table I

H = .15m			H = .21m			H = .24m		
u	$k=\frac{dp}{ds}_A$	c	u	$k=\frac{dp}{ds}_A$	c	u	$k=\frac{dp}{ds}_A$	c
8	1000	1132	8	2000	267	8	2000	537
12	3000	980	12	4000	755	12	5000	422
16	6000	462	16	8000	537	16	9000	566
20	9000	1132	20	12000	654	20	14000	706
24	14000	706	24	17000	778	24	11000	3129
28	18000	800	28	24000	924	28	28000	998
m/sec	N/m	N sec/m	m/sec	N/m	$N\frac{sec}{m}$	m/sec	N/m	$N\frac{sec}{m}$

At axle clearance $H = .15m$ $u = 16$ m/sec,

$k = 3000$ (N/m), $c = 1132 \frac{N\ sec}{m}$

are optimal values. So are

$u = 8$m/sec, $k = 2000$ N/m

$c = 267 \frac{N\text{-}sec}{m}$

for $H = .21m$

and $u = 12$m/sec, $k = 5000 \frac{N}{m}$,

$c = 422 \frac{N\ sec}{m}$

for $H = .24m$.

The improvement can be deduced from the comparison between fixed (assumed) suspension parameters and optimal parameter response, Figure 7. In closing it shall be mentioned that remarkable advantages can be realized with the proposed suspension control system.

1) Recommended speeds for optimal control can be posted at the dashboard (digital read-out)

2) For whatever reason the operator deems necessary he can switch to passive control or manual control, employing the control scheme based on (24), Table I.

Example

A vehicle negotiates a terrain described in [10] and displayed in Figure 1a. The terrain is Fourier transformed and axle and body accelerations are monitored for a vehicle forward speed of 21m/sec based on the assumed data given in Table 2. The terrain roughness is now reconstructed by direct integration, namely,

$$h(t) = \frac{ma}{k} x_a + (x_a dt)dt + x_b \frac{m_b}{k} \qquad (2a)$$

giving terrain figure 1b. The mean square value (10), (17) are then introduced into (18) where the permissible mean square suspension deflection amplitude $\bar{y}^2$ is given 1/9 of the available square axle clearance H^2 e.g.

$H = .21m$, $H^2 = .0442m^2$ $H^2/0 = .00049 = \bar{y}^2$;

$\bar{y} = .07$ in. For each set of parameters k, ζ, η^2 that

satisfies (18) there exists a forward speed u, that satisfies (19).

Table 2

Technical Data

Tandem Axle

Sprung Mass M: 4.087×10^3 kg per wheel set

Unsprung Mass m: 3.043×10^2 kg per wheel set

Sprung Mass

Natural frequency 60 cpm = 1 Hz; $\omega_n^2 = 39.48/\text{sec}^2$

Spring rate $k = 161{,}354$ kg/sec^2

Spring rate $K = 1{,}201{,}376$ kg/sec^2

Damping Constant $c = 17{,}976$ kg/sec

Damping Parameter $\xi = c/2\,(kM)^{1/2} = .7$

Wave Length L = 100m (m = meter)

Speed u = 25 m/sec (maximum), 20, 15, 10, 5 m/sec

Double amplitude of fundamental wave of length 100m: .1 m (10cm)

Axle clearance: (Static-Source)

9) Conclusions

Any person who is called upon to review a prospective design for possible adoption in the course of product planning, must ask whether the benefits gained outweigh the costs of the proposed suspension control. This judgement will depend on many factors most of which are unknown to the author of this report at this point in time.

In connection with such considerations it is fair to assess the expected performance of the system. Current expectations are that best results will be obtained in terrains for which power spectral desities vary between $.1m^2$/rad/m to $.0001m^2$/rad/m in the frequency range from 2 to 6 rad/meter. In terrains of substantially greater roughness manual control may be preferable and in terrains which are much smoother fixed suspension control may be more advantageous. Both modes could be made available in this control system. Also note that no changes in the parameter settings of the suspension will occur unless speed or terrain configurations or both change more than set threshold levels during the operation of the vehicle.

Actual perfromance increases to be expected would have to be determined at the time that design trade offs are being made. However, based on the simplicity of the system as compared to others being contemplated, an adaptive suspension control mechanism appears to offer the most attractive means of optimizing ride control in military vehicles.

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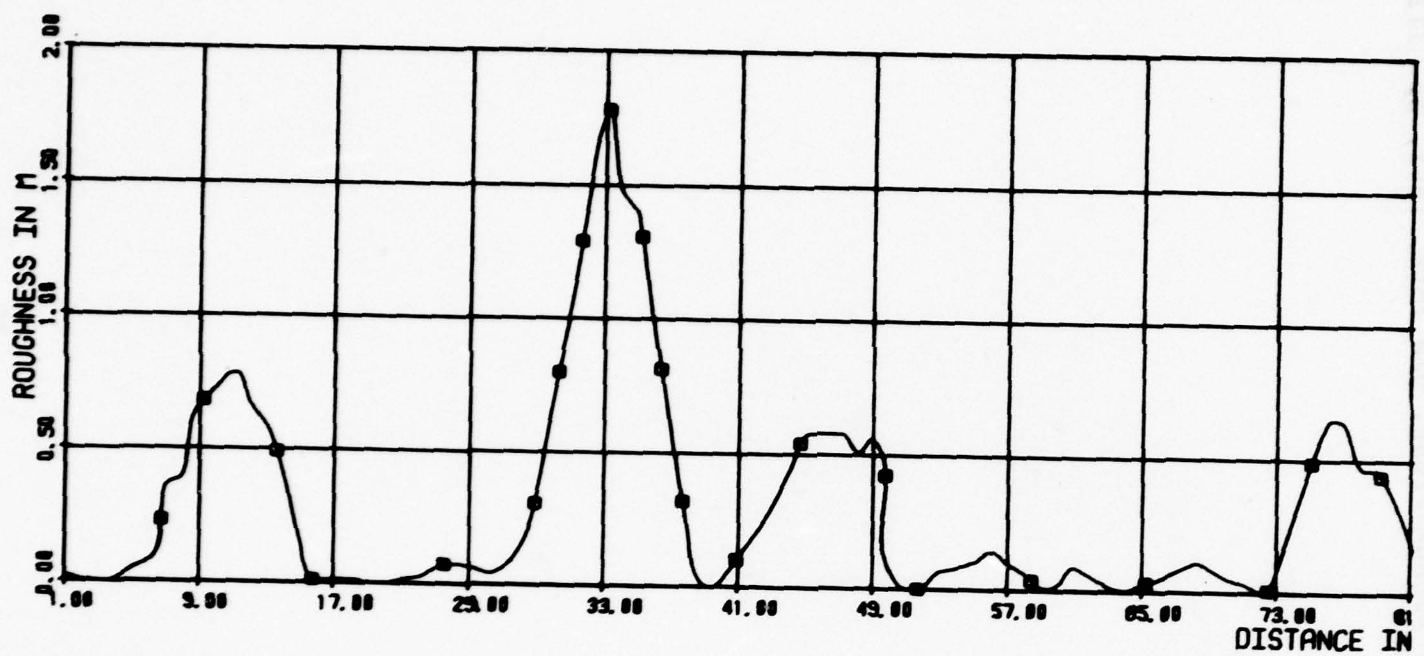
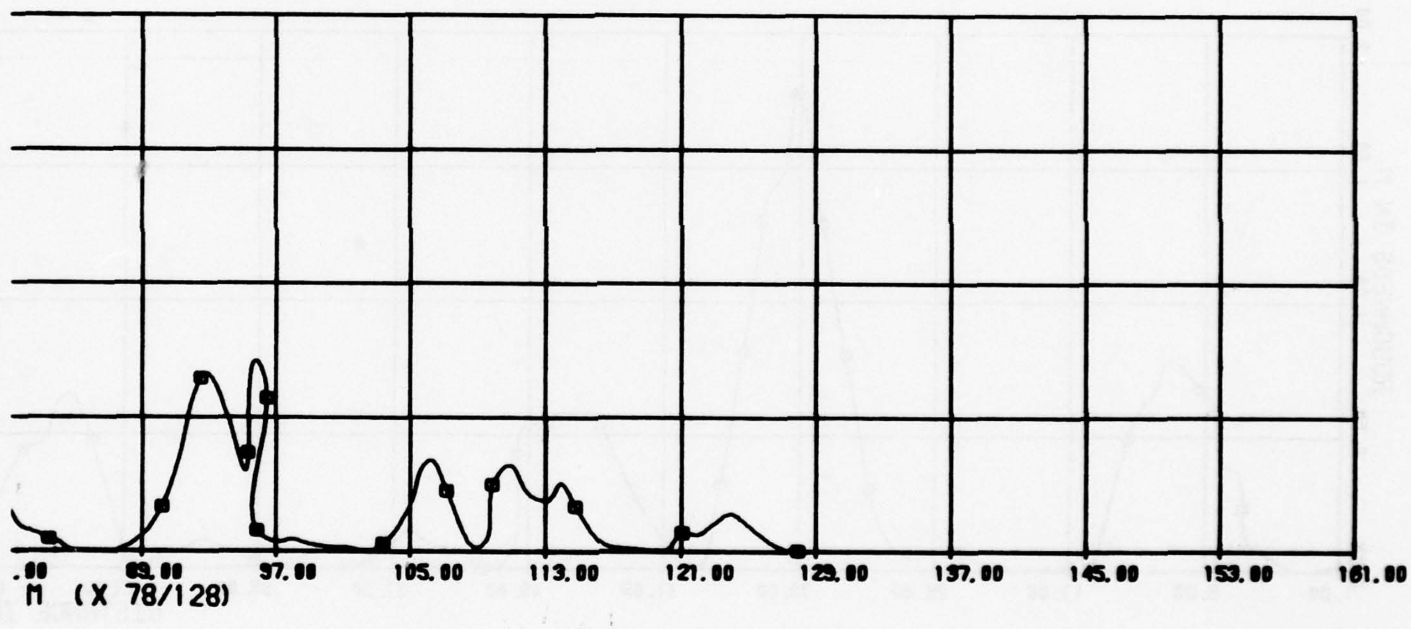
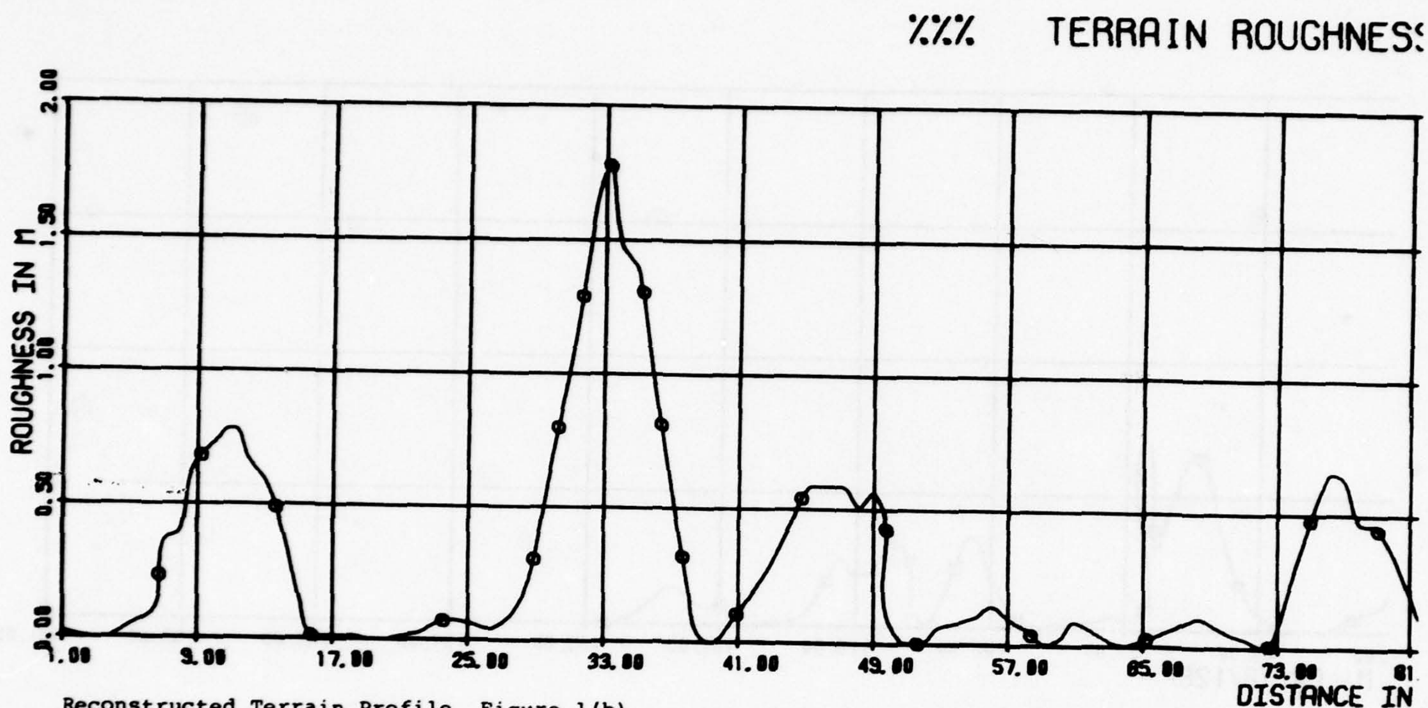


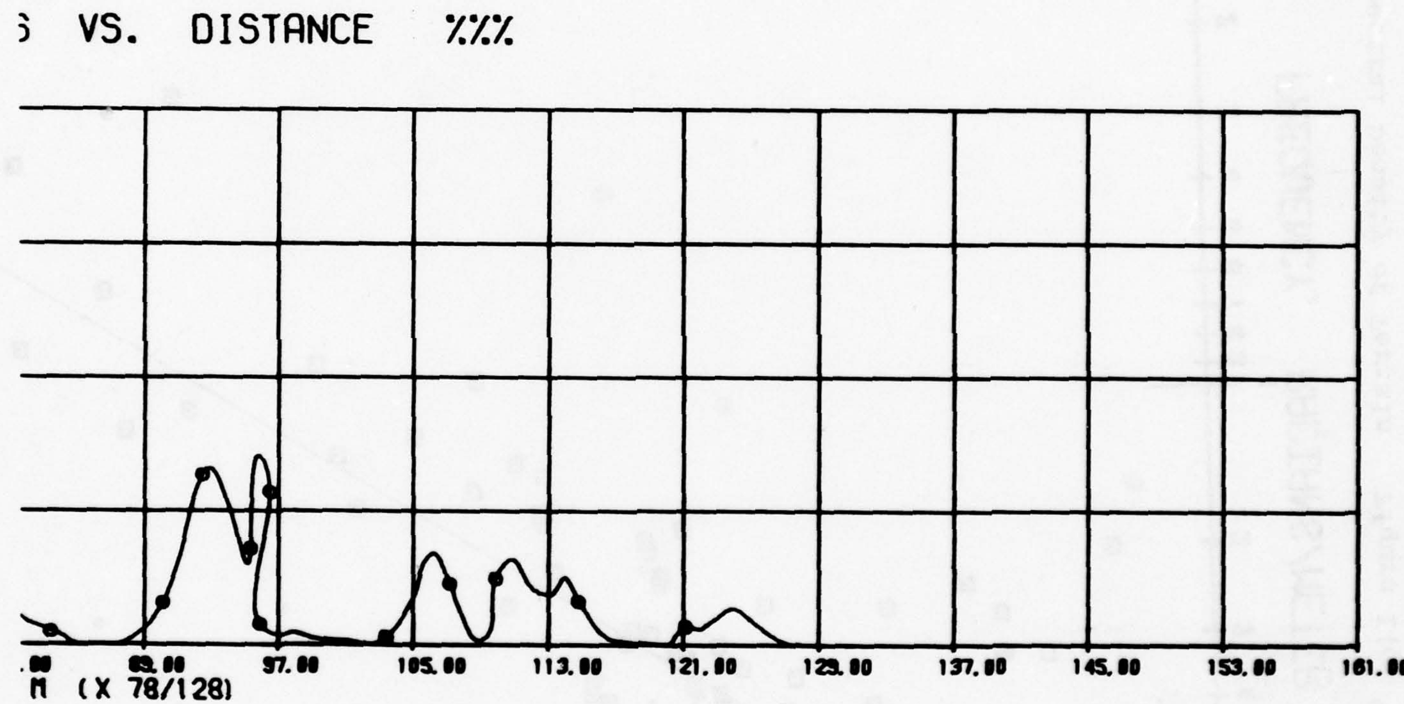
Actual Terrain Profile Figure 1(a)



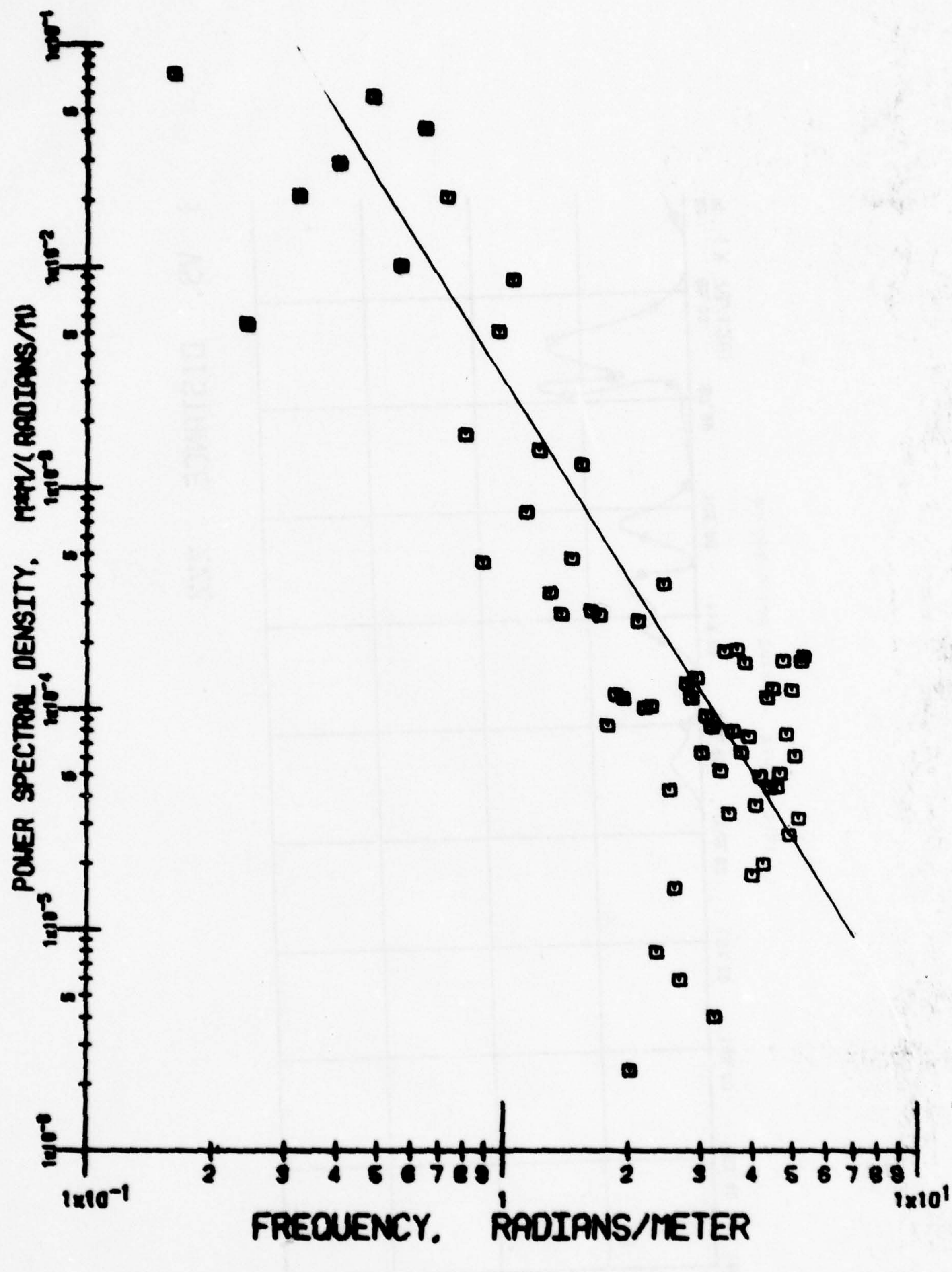
Actual Terrain Profile Figure 1(a)



Reconstructed Terrain Profile Figure 1(b)



Recontructed Terrain Figure 1(b)



Power Spectral Density of Terrain Figure 1(c)

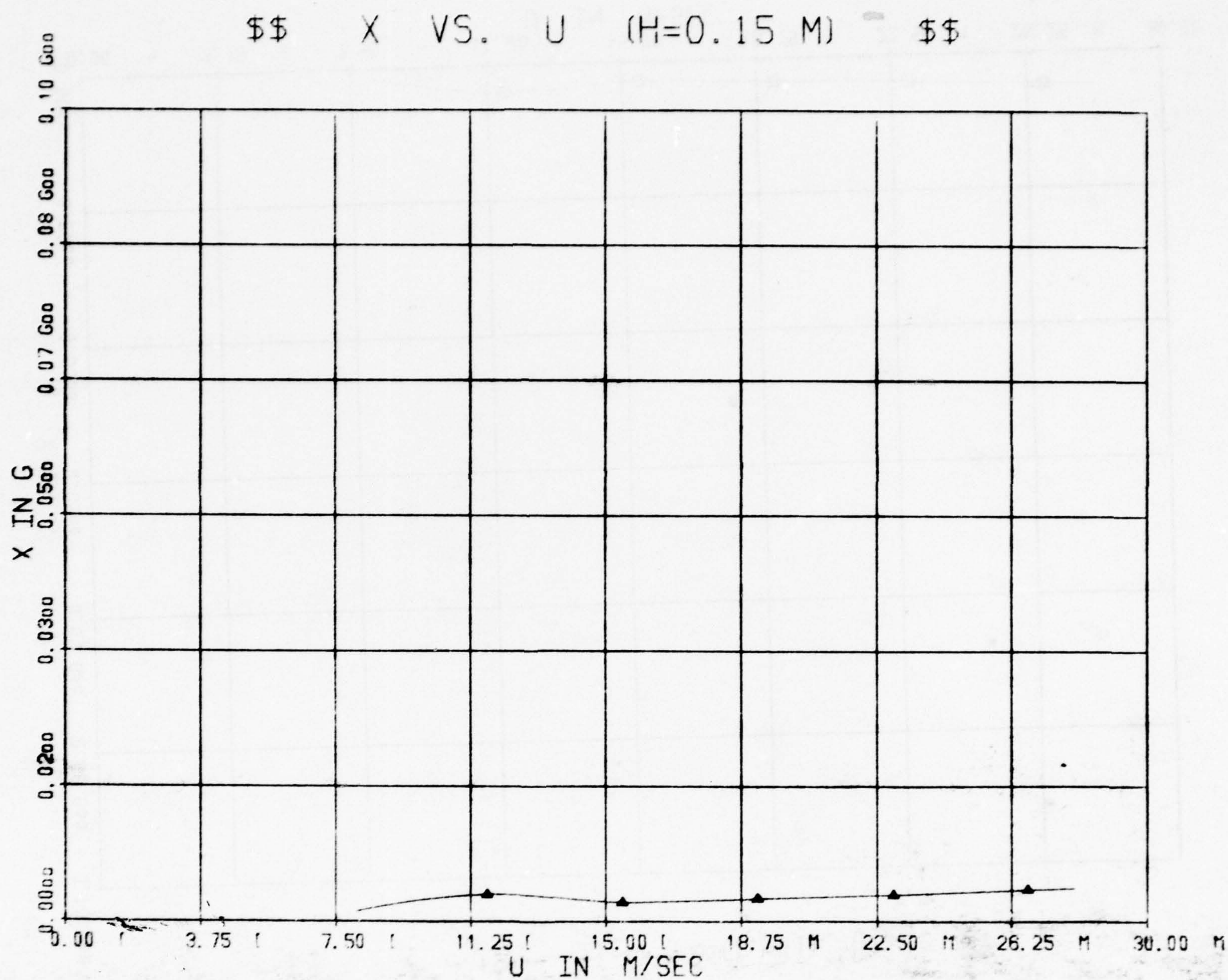

$$ X VS. U (H=0.15 M) $$
X IN G
0.10 Goo
0.08 Goo
0.07 Goo
0.0500
0.0300
0.0200
0.0000
0.00
3.75
7.50
11.25
15.00
18.75 M
22.50 M
26.25 M
30.00 M
U IN M/SEC

Figure 2

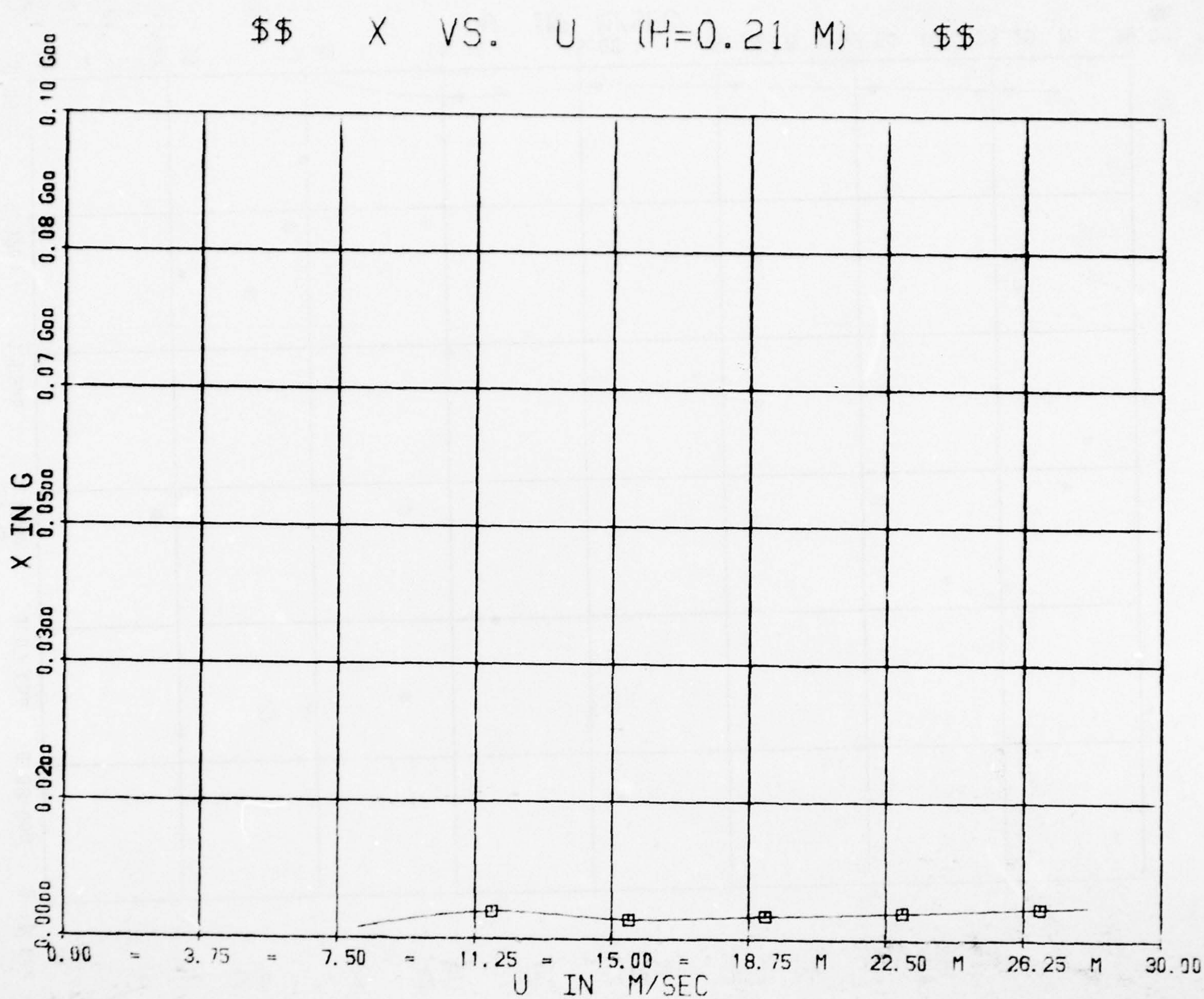

$$ X VS. U (H=0.21 M) $$
X IN G
0.10 Goo
0.08 Goo
0.07 Goo
0.05oo
0.03oo
0.02oo
0.00oo
0.00 = 3.75 = 7.50 = 11.25 = 15.00 = 18.75 M 22.50 M 26.25 M 30.00
U IN M/SEC

Figure 3

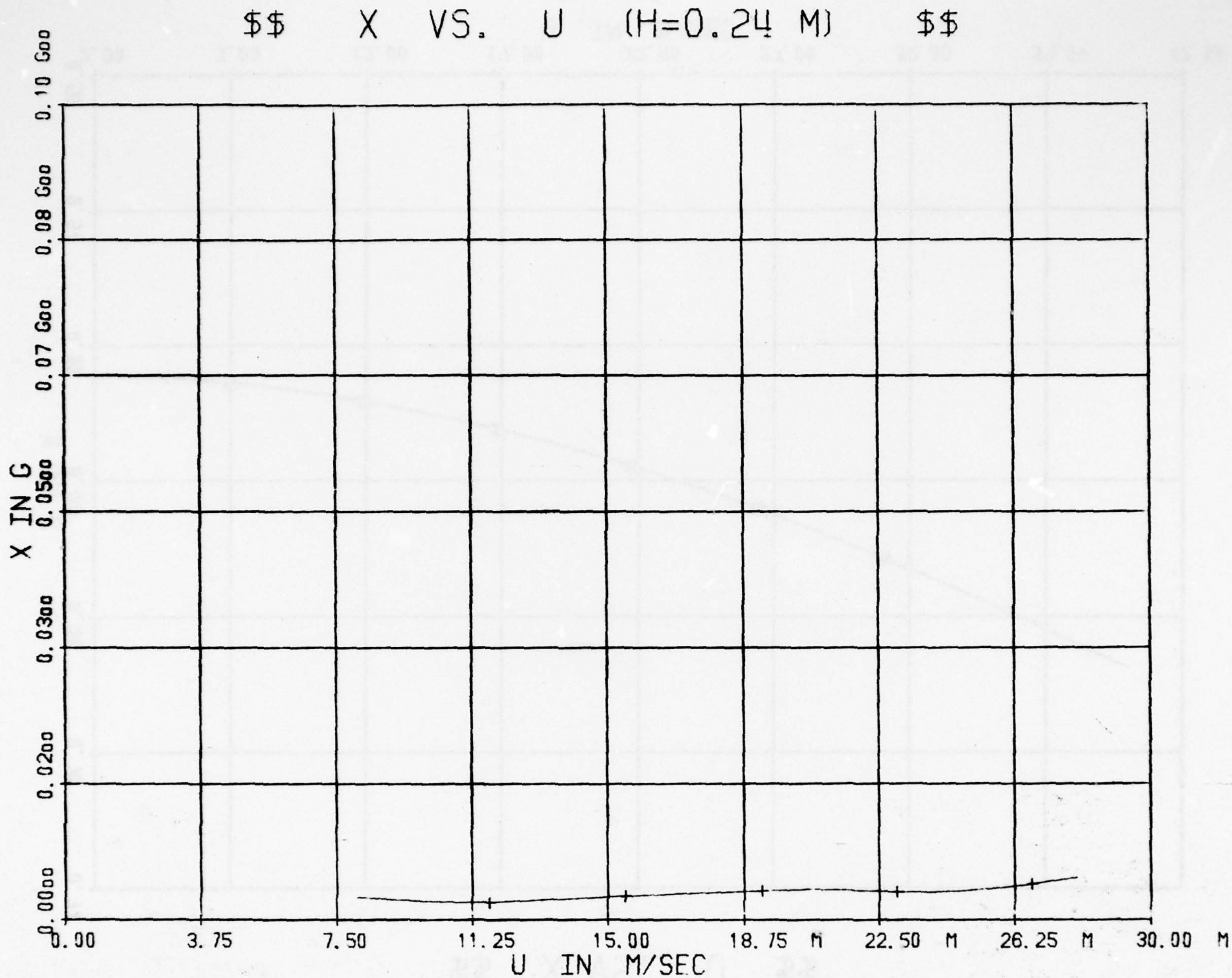

$$ X VS. U (H=0.24 M) $$
X IN G
0.10 Goo
0.08 Goo
0.07 Goo
0.0500
0.0300
0.0200
0.0000
0.00
3.75
7.50
11.25
15.00
18.75 M
22.50 M
26.25 M
30.00 M
U IN M/SEC

Figure 4

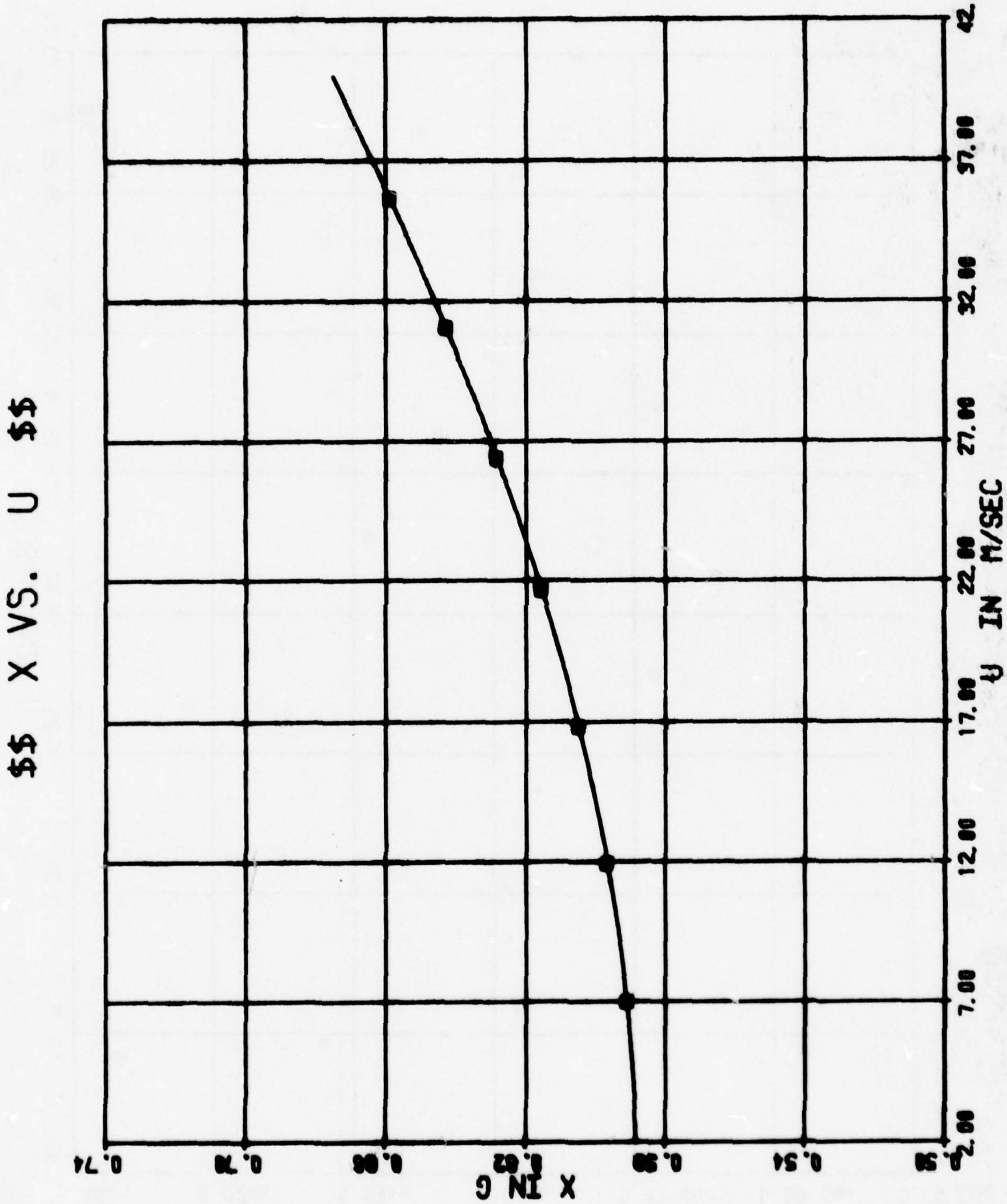

$$ X VS. U $$
U IN M/SEC
X IN G
2.00
7.00
12.00
17.00
22.00
27.00
32.00
37.00
42.00
0.50
0.54
0.58
0.62
0.66
0.70
0.74

Figure 5

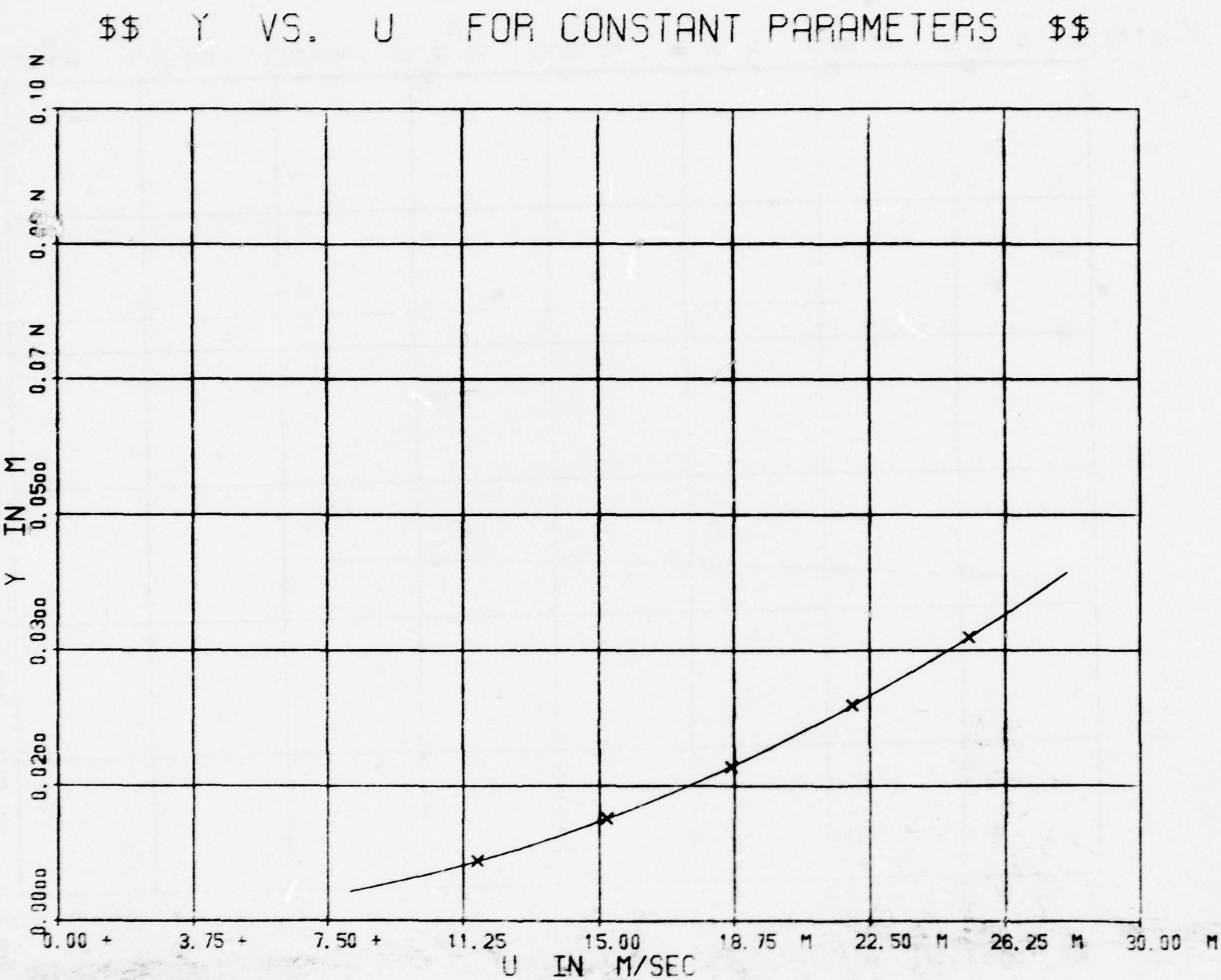

$$ Y VS. U FOR CONSTANT PARAMETERS $$
Y IN M
0.10 N
0.07 N
0.0500
0.0300
0.0200
0.0000
0.00 +
3.75 +
7.50 +
11.25
15.00
18.75 M
22.50 M
26.25 M
30.00 M
U IN M/SEC

Figure 6

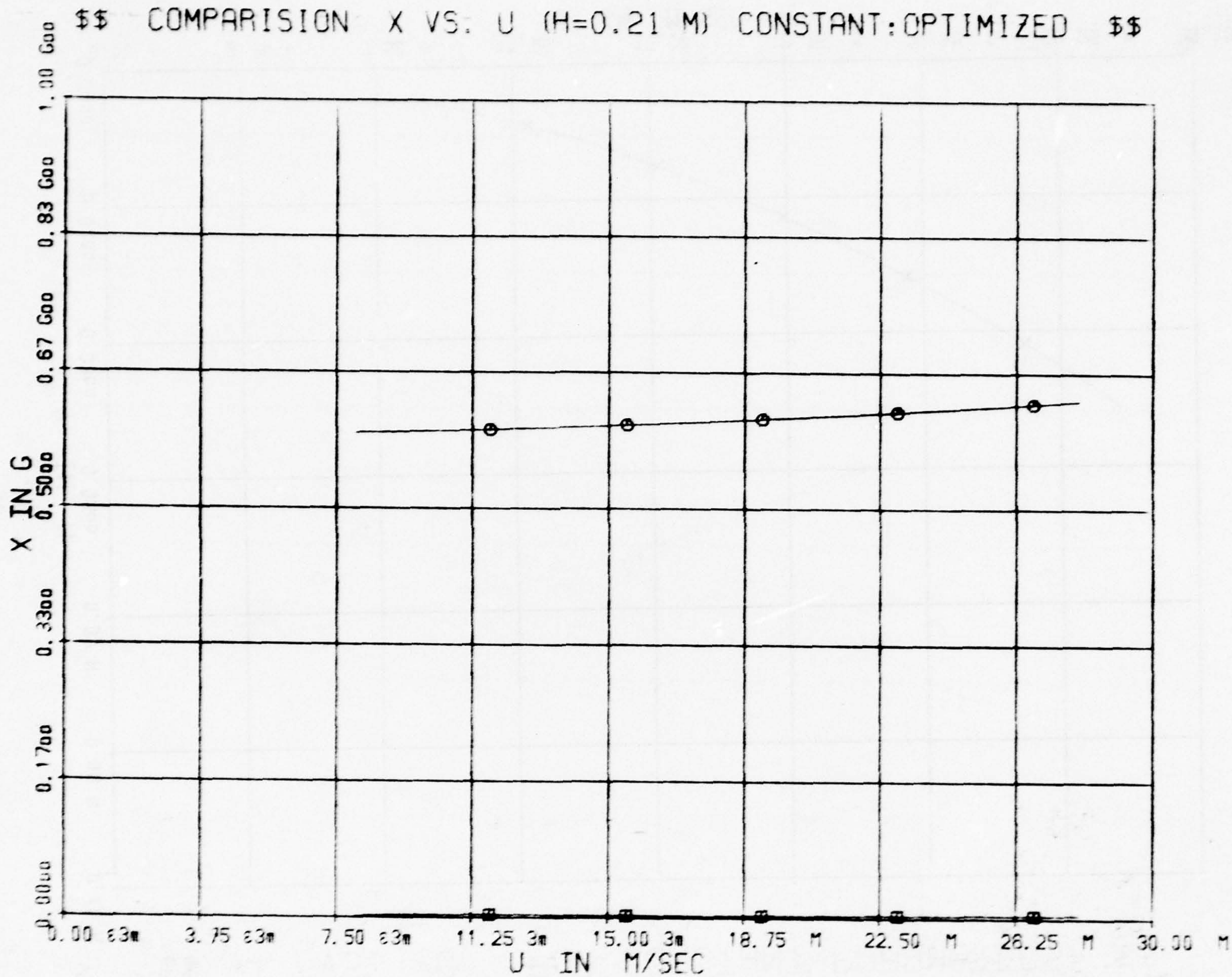

$$ COMPARISION X VS. U (H=0.21 M) CONSTANT:OPTIMIZED $$
X IN G
1.00 Goo
0.83 Goo
0.67 Goo
0.5000
0.3300
0.1700
0.0000
0.00 ε3m
3.75 ε3m
7.50 ε3m
11.25 3m
15.00 3m
18.75 M
22.50 M
26.25 M
30.00 M
U IN M/SEC

Figure 7

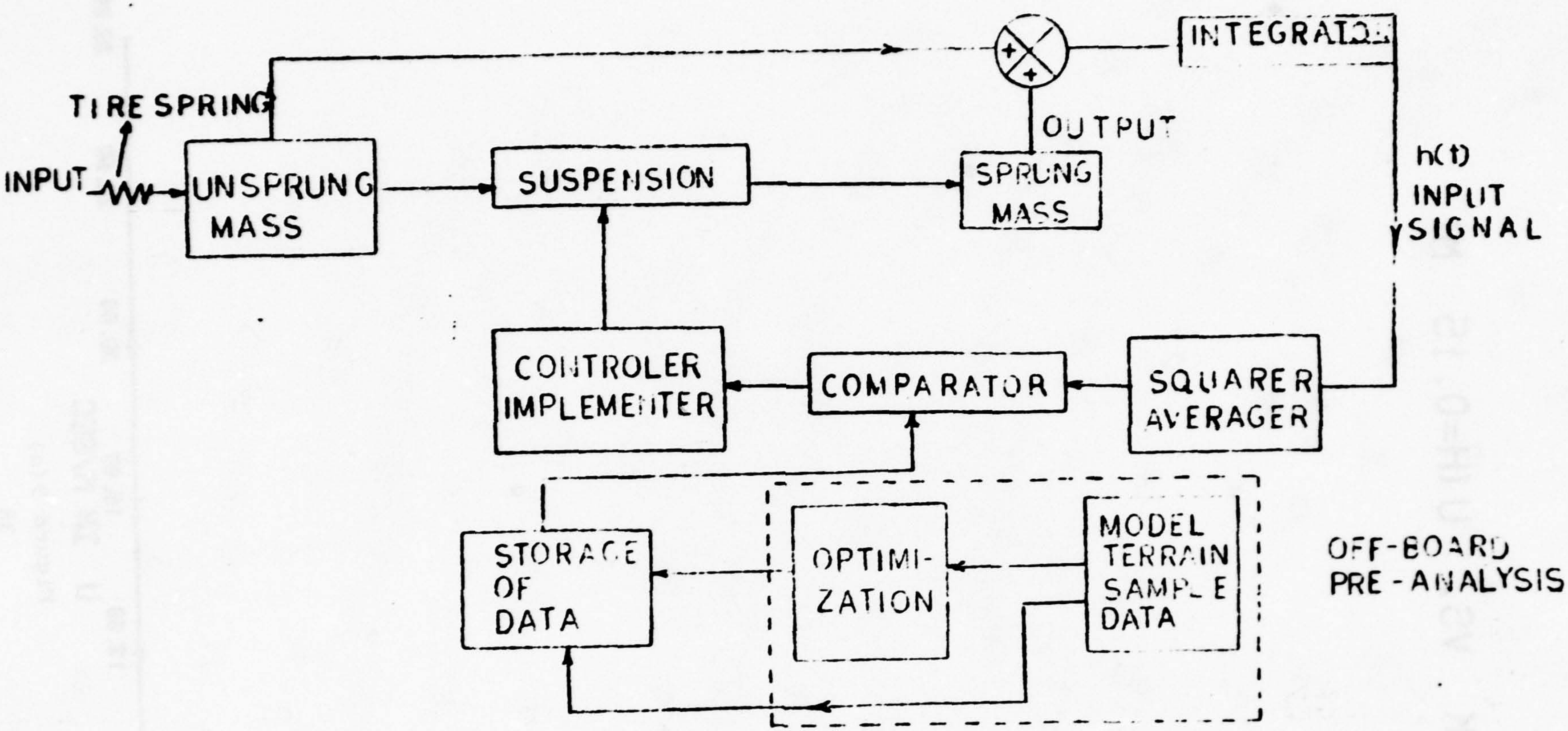


FIG. 8 BLOCK DIAGRAM OF ADAPTIVE CONTROL

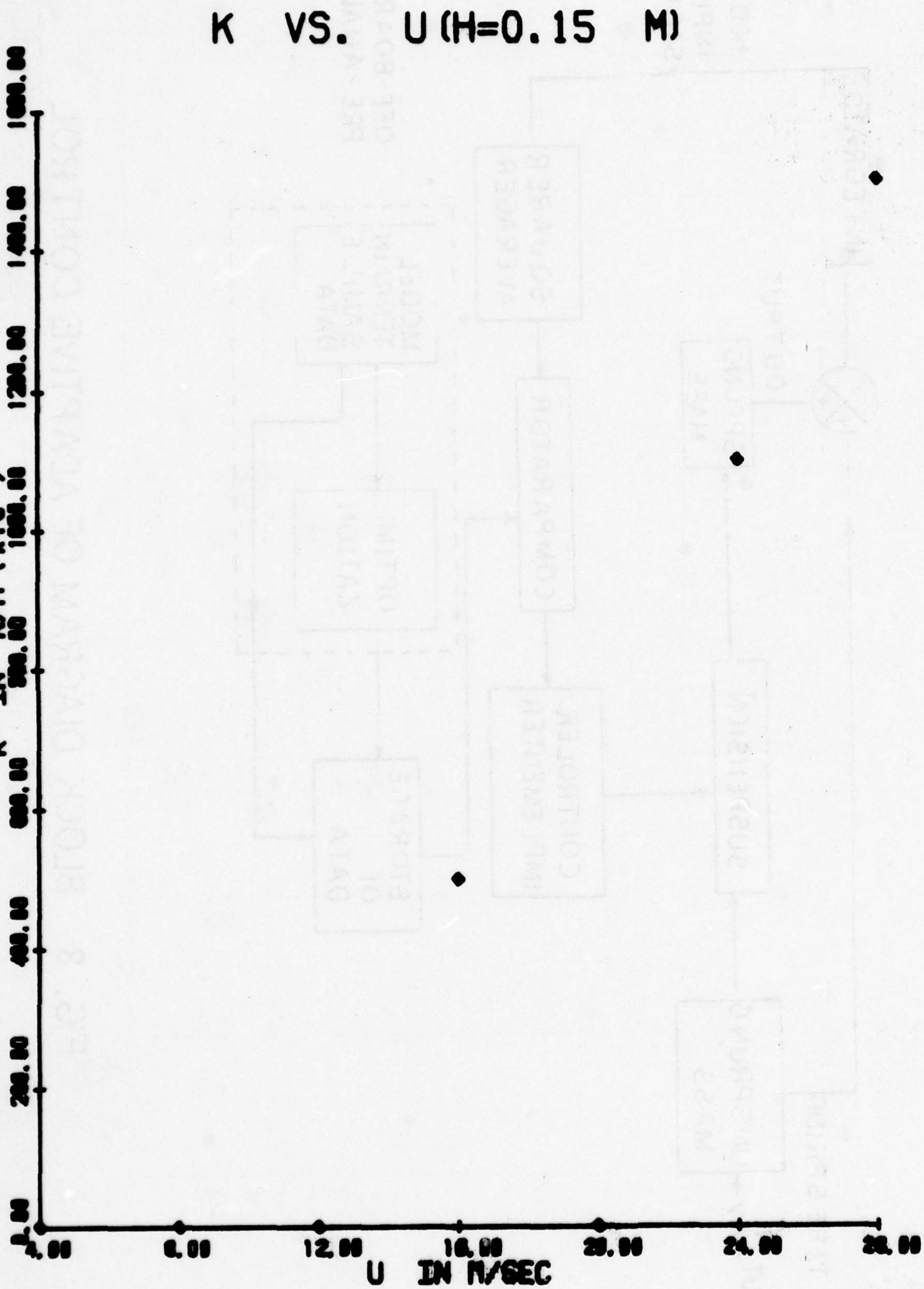

K VS. U (H=0.15 M)
K IN N/M (x10^-1)
0.00
200.00
400.00
600.00
800.00
1000.00
1200.00
1400.00
1600.00
4.00
8.00
12.00
16.00
20.00
24.00
28.00
U IN M/SEC

Figure 9(a)

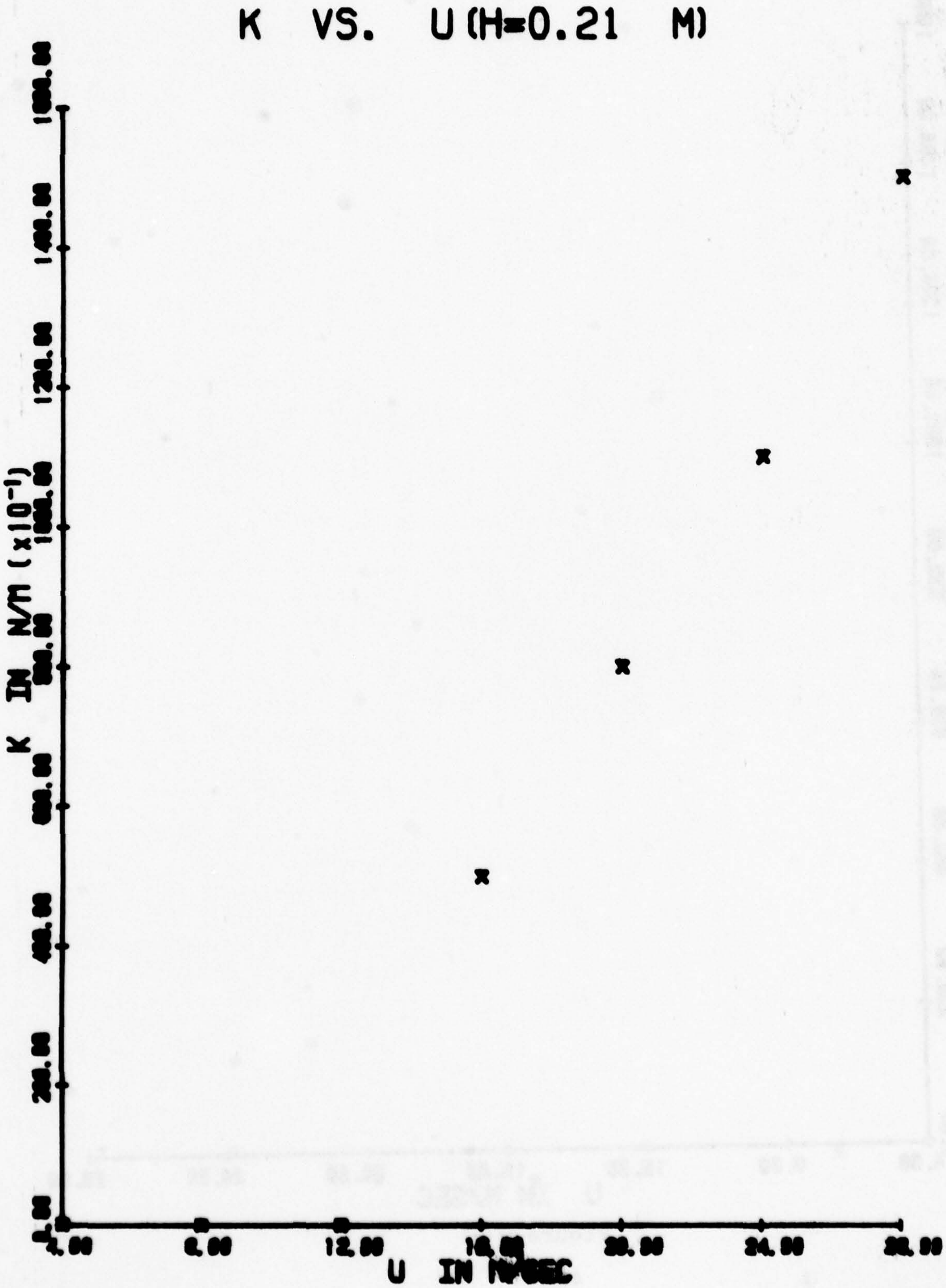

K VS. U(H=0.21 M)
K IN N/M (x10^-1)
U IN M/SEC
1600.00
1400.00
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
8.00
12.00
16.00
20.00
24.00
28.00

Figure 9(b)

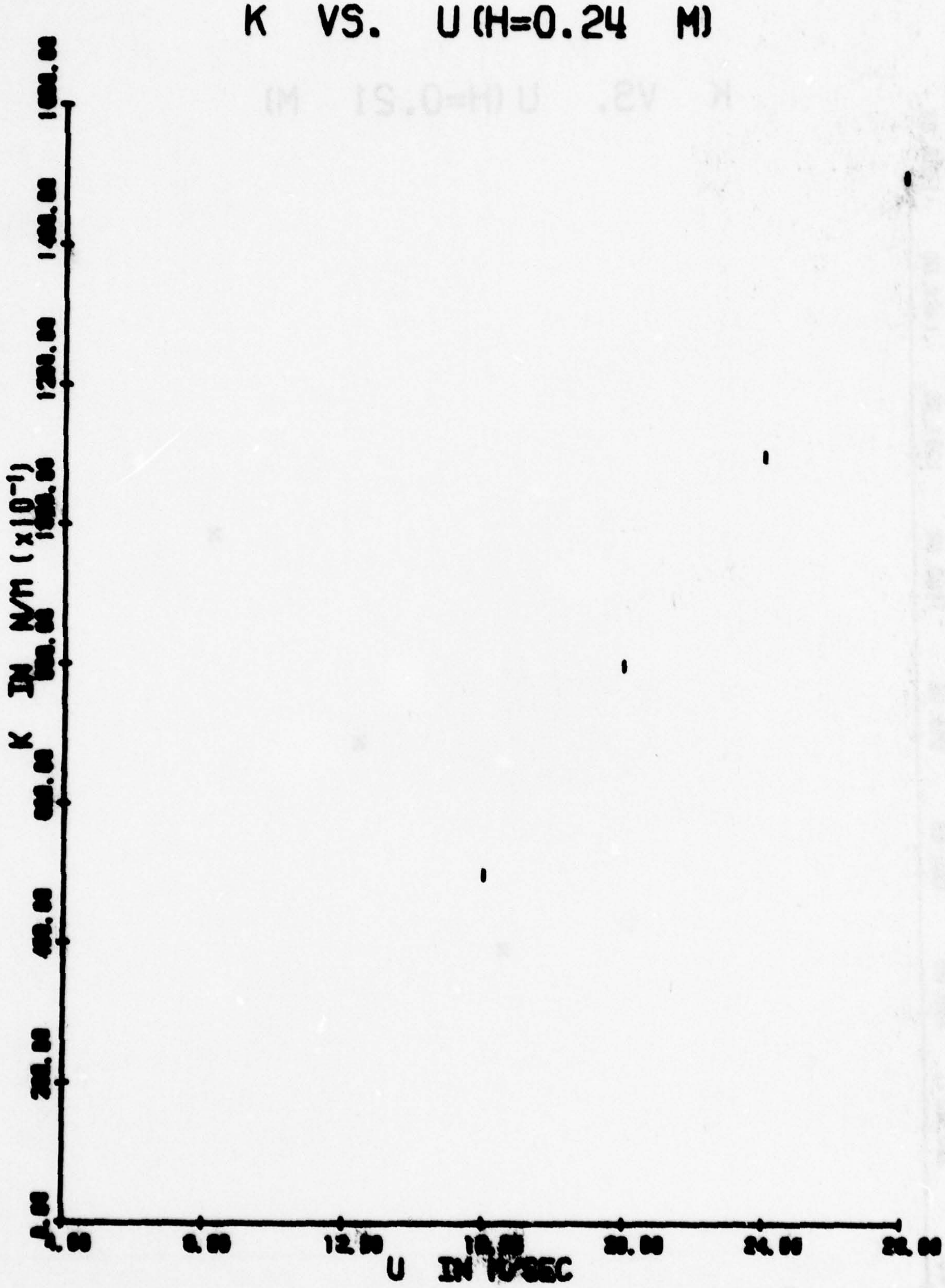


Figure 9(c)

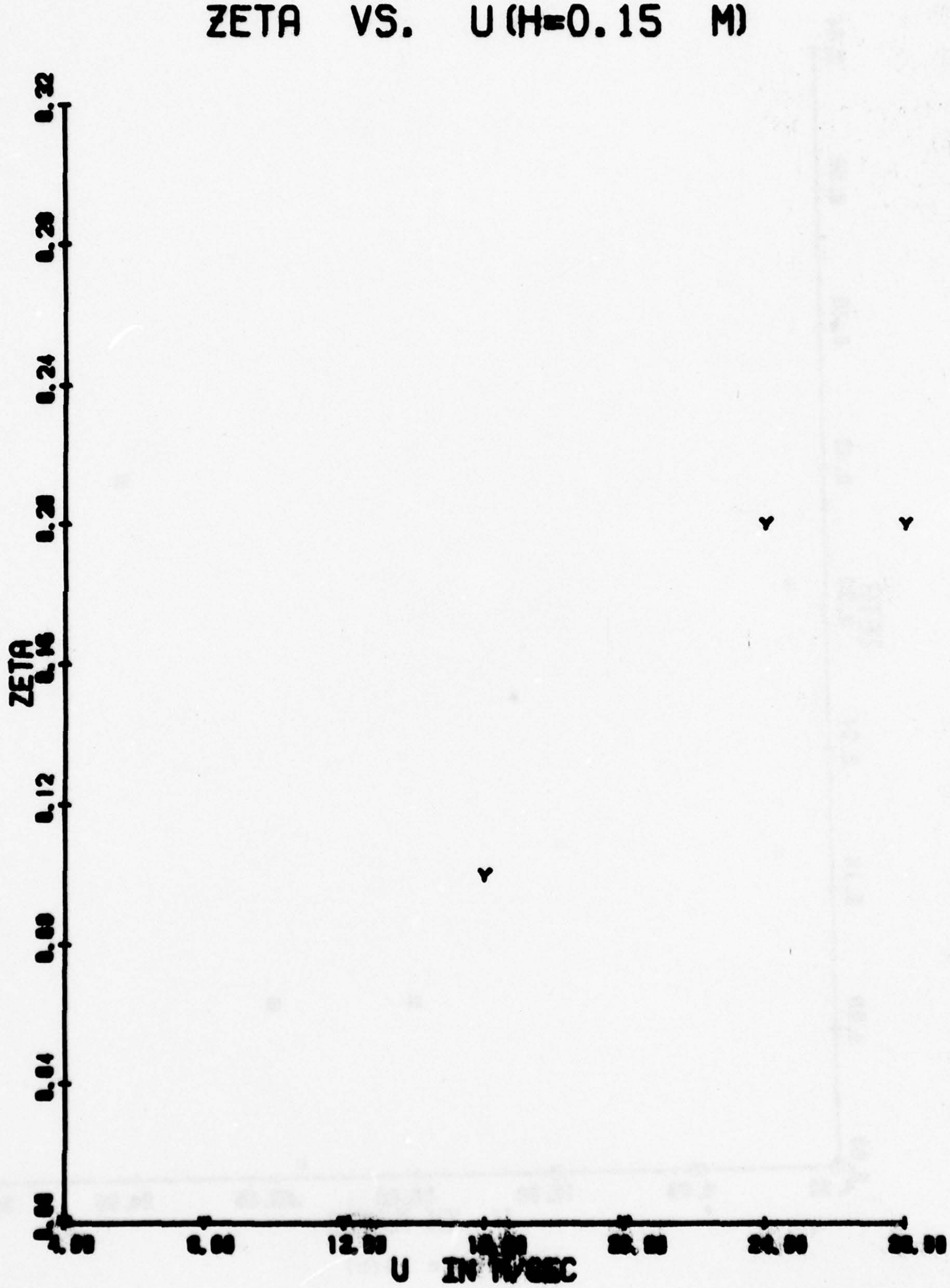

ZETA VS. U(H=0.15 M)
ZETA
U IN M/SEC
0.32
0.28
0.24
0.20
0.16
0.12
0.08
0.04
0.00
4.00
8.00
12.00
16.00
20.00
24.00
28.00

Figure 10(a)

ZETA VS. U (H=0.21 M)

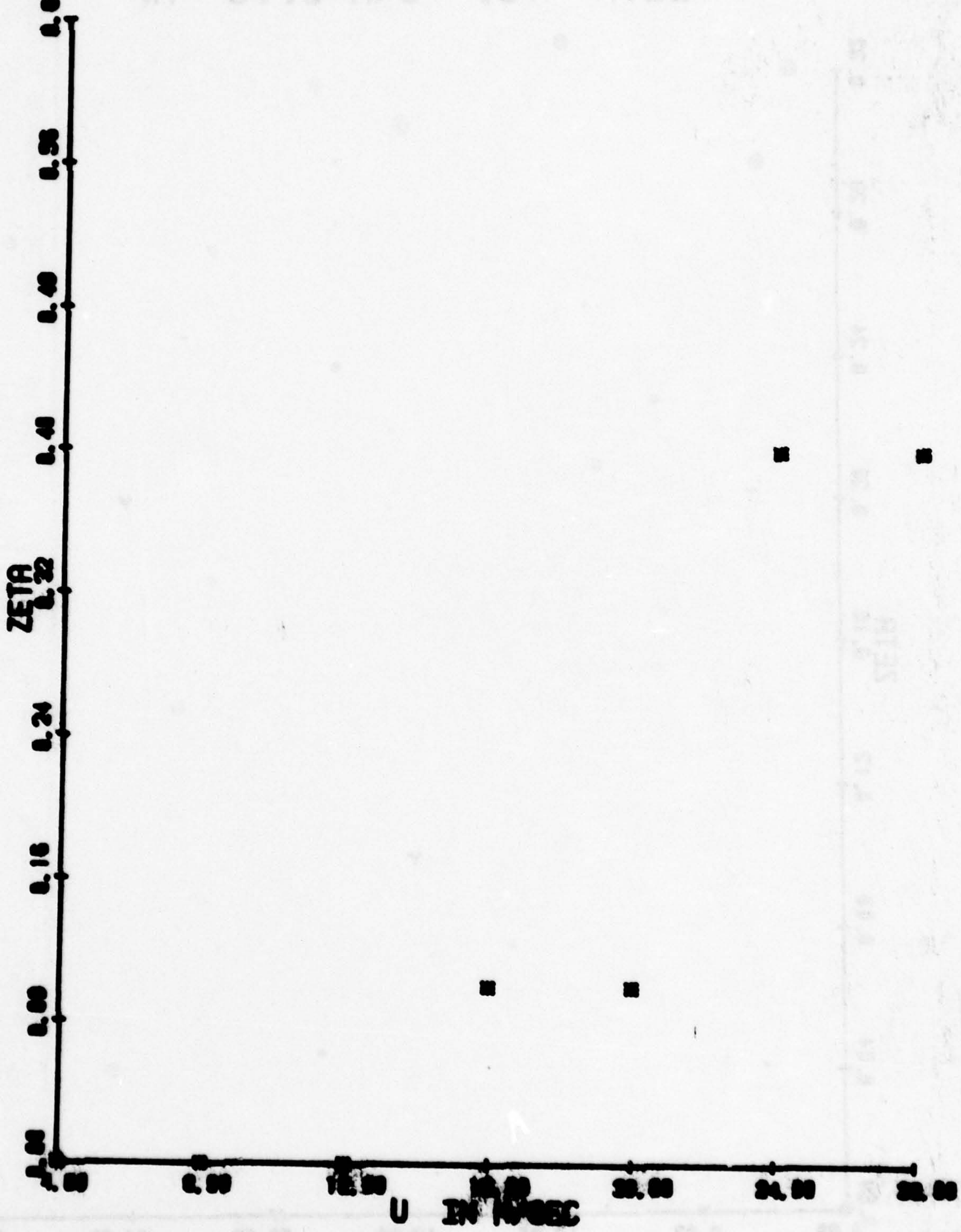


Figure 10(b)

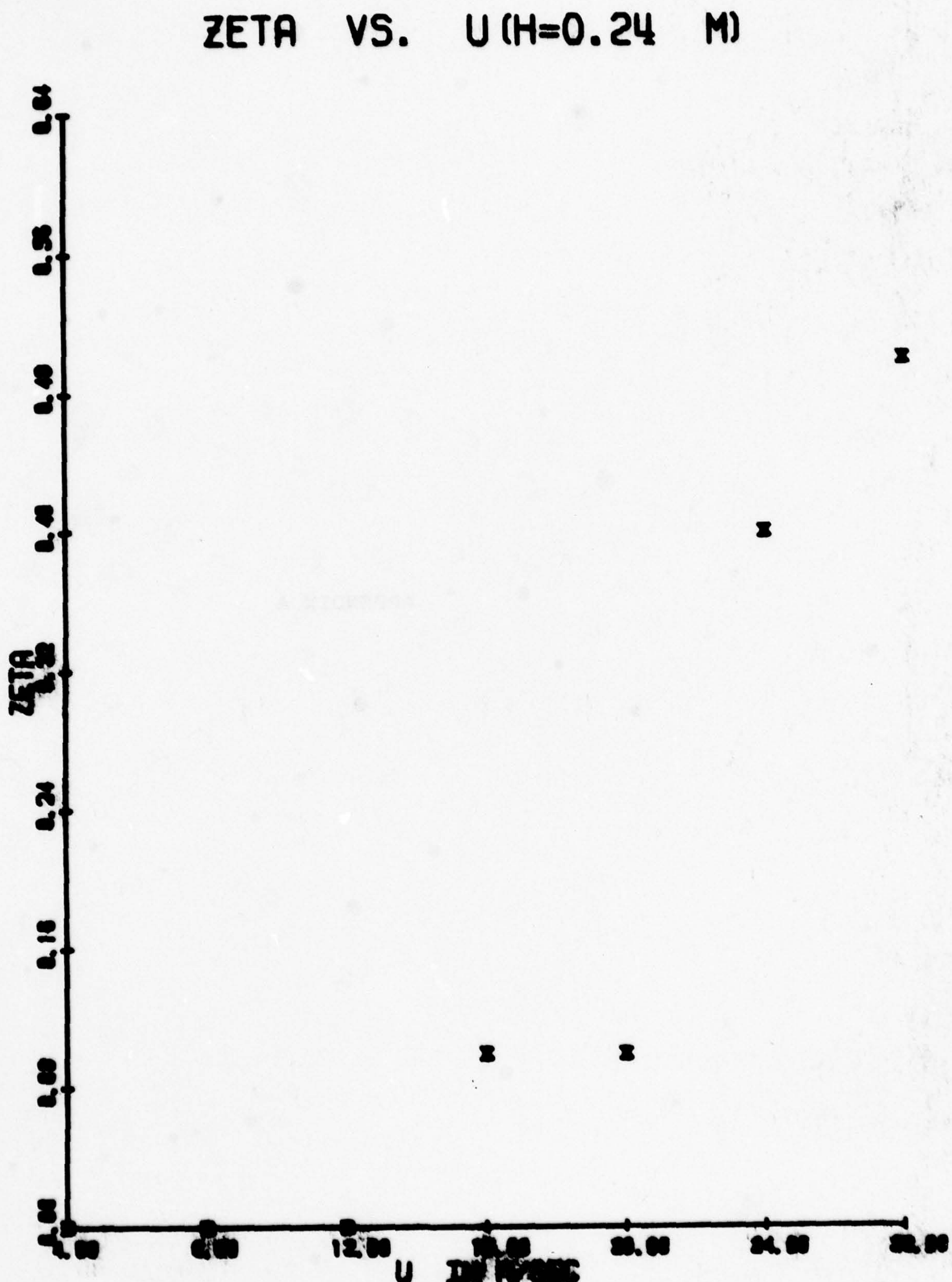


Figure 10(c)

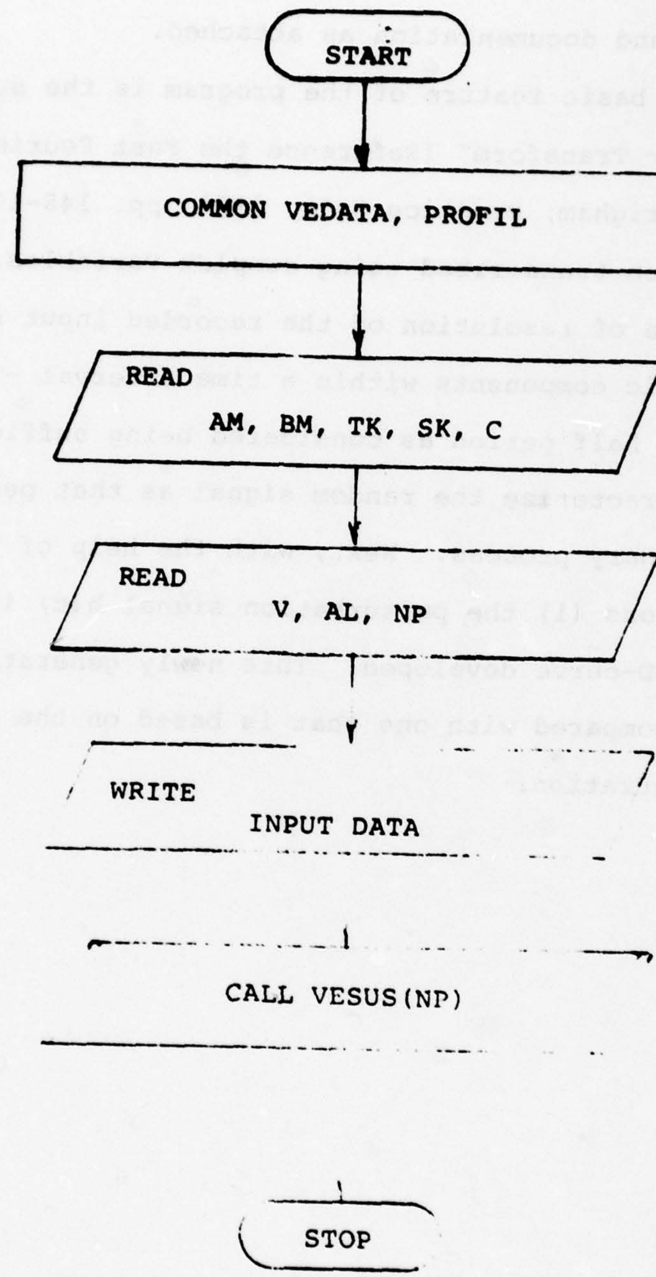
APPENDIX A

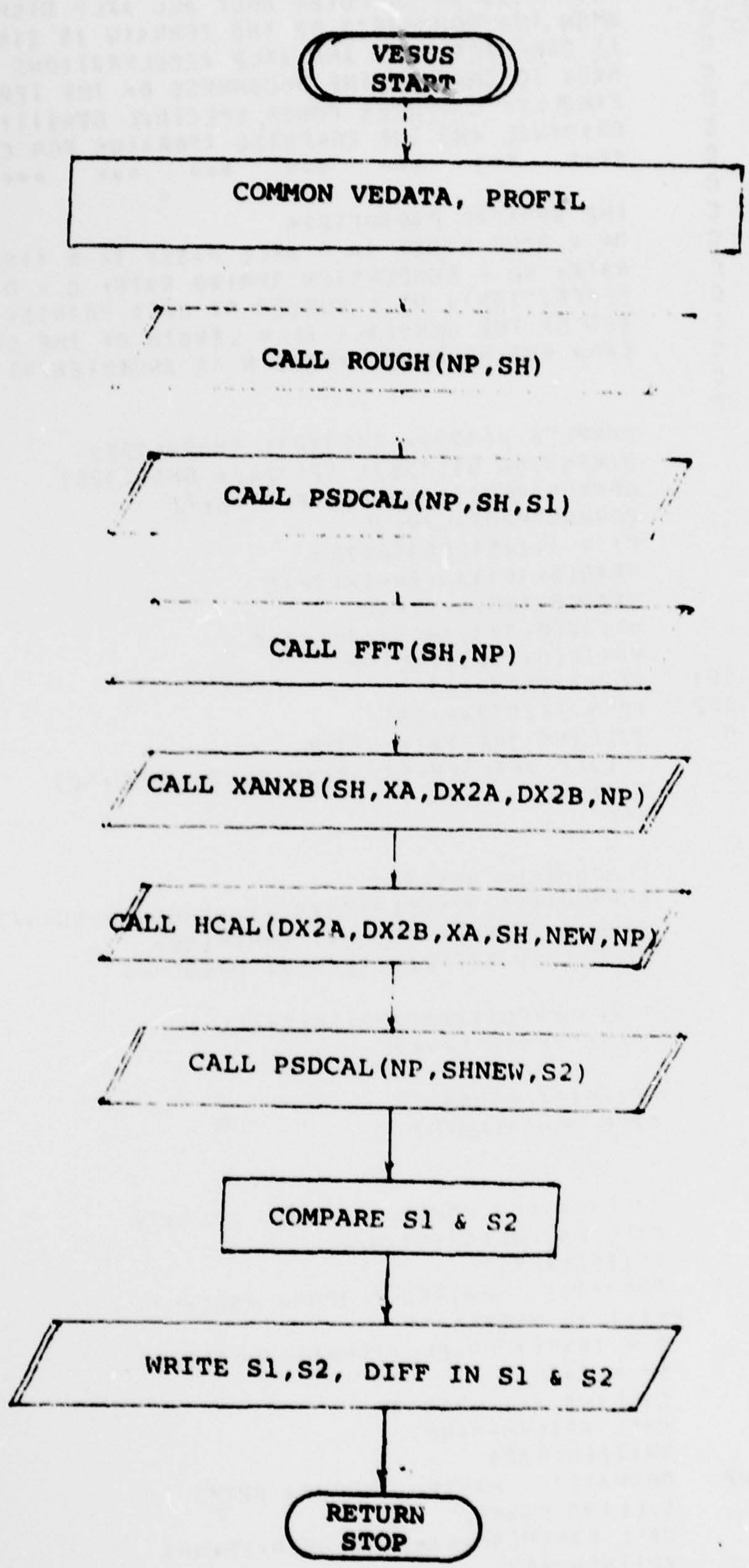
Appendix A

A program has been established containing the program steps and documentation as attached.

The basic feature of the program is the subroutine "Fast Fourier Transform" (Reference the Fast Fourier Transform by E.O. Brigham, Prentice Hall, 1974, pp. 148-171). The program has been transcribed using complex variables. It serves the purpose of resolution of the recorded input signals into its harmonic components within a time interval $-T<t<T$ wherein T is the half period as considered being sufficient in duration to characterize the random signal as that pertaining to a stationary process. Next, with the help of the system equations (1) the perturbation signal h(t) is regenerated and the PSD-curve developed. This newly generated ensemble is then compared with one that is based on the actual terrain configuration.

FLOW DIAGRAM




VESUS
START
COMMON VEDATA, PROFIL
CALL ROUGH(NP,SH)
CALL PSDCAL(NP,SH,S1)
CALL FFT(SH,NP)
CALL XANXB(SH,XA,DX2A,DX2B,NP)
CALL HCAL(DX2A,DX2B,XA,SH,NEW,NP)
CALL PSDCAL(NP,SHNEW,S2)
COMPARE S1 & S2
WRITE S1,S2, DIFF IN S1 & S2
RETURN
STOP

```
C     THIS PROGRAM COMPUTES BODY AND AXLE DISPLACEMENTS
C     WHEN THE ROUGHNESS OF THE TERRAIN IS GIVEN, THEN
C     IT COMPUTES BODY AND AXLE ACCELERATIONS AND GOES
C     BACK TO COMPUTE THE ROUGHNESS OF THE TERRAIN. IT
C     FINALLY, COMPUTES POWER SPECTRAL DENSITIES OF THE
C     ORIGINAL AND THE COMPUTED TERRAINS FOR COMPARISION
C     ****  ***  ***  ***  ***  ***  ***  ***  *
C
C     THE VEHICAL PARAMETERS
C     BM = BODY MASS, AM = AXLE MASS, TK = TIRE SPRING
C     RATE, SK = SUSPENSION SPRING RATE, C = DAMPING
C     COEFFICIENT, NP = NUMBER OF DATA POINTS, V = SP
C     EED OF THE VEHICAL, AL = LENGTH OF THE SPAN,
C     (FOR FFT NP=2**N, WHERE N IS AN INTEGER)
C
C
      COMPLEX H(128), SH(128), SHNEW(128)
      DIMENSION S1(128), S2(128), DPSD(128)
      COMMON/VEDATA/AM,BM,TK,SK,C,PI
      COMMON/PROFIL/V,AL
      PI = 3.14159265358979З
      READ(5,101)AM,BM,TK,SK,C
      READ(5,102)V,AL,NP
      WRITE(6,101)AM,BM,TK,SK,C
      WRITE(6,102)V,AL,NP
101   FORMAT(5F10.6)
102   FORMAT(2F10.6,I3)
C     CALLING THE MAIN VESUS
        CALL VESUS(H,S1,S2,SH,SHNEW,DPSD,NP)
      STOP
      END
C
C     SUBROUTINE VESUS
      SUBROUTINE VESUS(H,S1,S2,SH,SHNEW,DPSD,NP)
      COMPLEX H(NP), SH(NP), SHNEW(NP)
      DIMENSION S1(NP), S2(NP), DPSD(NP)
C
      COMMON/VEDATA/AM,BM,TK,SK,C,PI
      COMMON/PROFIL/V,AL
C
C      CALLING ROUGH
      CALL ROUGH(NP,H)
C
C
C     CALLING FOR POWER SPECTRAL DENSITY
      CALL PSDCAL(SH,S1,NP)
      WRITE(6,801)
801   FORMAT('   PASSED THROUGH PSDCAL')
C    PRINT IF NECESSARY
      N = IFIX(ALOG(FLOAT(NP))/ALOG(2.))
      NP = 2**N
C     CALLING FFT PROGRAM
      CALL FFT(SH,N,NP)
      WRITE(6,802)
802   FORMAT('   PASSED THROUGH FFT')
C     CALLING XANKB
      CALL XANXB(SH,XA,DX2A,DX2B,XB,NP)
      WRITE(6,803)
```

```
  803   FORMAT('   PASSED THROUGH XANKB')
  C    PRINT IF NECESSARY
  C     CALLING HCAL
        CALL HCAL(DX2A,DX2B,XA,SHNEW,NP)
  C     CALLING PSDCAL SHNEW
        CALL PSDCAL(SHNEW,S2,NP)
  C    PRINT IF NECESSARY
        DO 1 J=1,NP
  1     DPSD(J) = S1(J) - S2(J)
        WRITE(6,201) (S1(I),S2(I),DPSD(I),I=1,NP)
  201   FORMAT(' ',8E15.6)
        RETURN
        END
  C
  C     SUBROUTINE ROUGH STARTS
         SUBROUTINE ROUGH(N,H)
        DIMENSION H1(1024)
        COMPLEX H(N)
        REAL*4 FMT(1)/'*'/
        READ(5,FMT)(H1(I),I=1,N)
        DO 1 I=1,N
        H1(I) = H1(I)*0.3048
  1     H(I) = CMPLX(H1(I),0.0)
        WRITE(6,2) (H(I),I=1,10)
  2      FORMAT(6E15.6)
        RETURN
        END
  C
  C     SUBROUTINE PSDCAL
        SUBROUTINE PSDCAL(H,S,NP)
        COMPLEX H(NP)
        DIMENSION S(NP)
        COMMON/VEDATA/AN,BN,IK,SK,C,PI
        COMMON/PROFIL/V,AL
        OMEGA = 2.*PI*V/AL
        ETA = OMEGA*SQRT(BN/SK)
        DO 1 I=1,NP
  1     S(I) = H(I)*CONJG(H(I))/(2.*ETA)
        RETURN
        END
  C
  C     SUBROUTINE FFT
        SUBROUTINE FFT(A,N,NP)
        COMPLEX A(NP),U,W,T,CMPLX
  C     DIVIDING ALL ELEMENTS BY NP
        DO 1 I=1,NP
  1     A(I) = A(I)/NP
  C     REORDERING THE SEQUENCE
        NPD2 = NP/2
        NPM1 = NP - 1
        DO 4 L = 1,NPM1
        IF(L.GE.J)GO TO 2
        T = A(J)
        A(J) = A(L)
        A(L) = T
  2     K=NPD2
  3     IF(K.GE.J)GO TO 4
        J = J - K
        K = K/2
        GO TO 3
  4     J = J+K
```

```
>      C     COMPUTATION OF FFT
>            PI = 3.14592653589793
>            DO 6 M=1,N
>            U = (1.0,0.0)
>            ME = 2**M
>            K = ME/2
>            W = CMPLX(COS(PI/K), -SIN(PI/K))
>            DO 6 J=1,K
>            DO 5 L=J,NR,ME
>            LPK = L+K
>            T = A(LPK)*U
>            A(LPK) = A(L) - T
>      5     A(L) = A(L)+T
>      6     U = U*W
>            RETURN
>            END
>      C
>      C      SUBROUTINE XANXB
>            SUBROUTINE XANXB(H,XA,DX2A,DX2B,XB,NP)
>            COMPLEX H(NP),XA(NP),XB(NP),DX2A(NP),DX2B(NP)
>            COMPLEX A(2,2),CMPLX
>            COMMON/VEDATA/AM,BM,TK,SK,C,PI
>            COMMON/PROFIL/V,AL
>      C
>            AMU = TK/SK
>            AMU1 = AM/BM
>            OMEGA = 2.*PI*V/AL
>            SRT = SQRT(BM/SK)
>            ETA = OMEGA*SRT
>            GETA = C/(2.*SRT)
>            DO 1 I=1,NP
>            AIM = 2.*GETA*ETA*I
>            ARE = (ETA*I)**2
>            A(1,1) = CMPLX(1.-ARE,AIM)
>            A(1,2) = CMPLX(-1.,-AIM)
>            A(2,2) = CMPLX(1.+AMU-AMU1*ARE,AIM)
>            DELTA = A(1,1)*A(2,2) - A(1,2)*A(1,2)
>            XA(I) = A(1,1)*AMU*H(I)/DELTA
>            XB(I) = -A(1,2)*AMU*H(I)/DELTA
>            ETA2 =ETA*ETA
>            ETA4 = ETA2*ETA2
>            DX2A(I) = ETA4*XA(I)
>            DX2B(I) = ETA4*XB(I)
>      1     CONTINUE
>            RETURN
>            END
>      C
>      C      SUBROUTINE HCAL(DX2A,DX2B,XA,H,NP)
>            SUBROUTINE HCAL(DX2A,DX2B,XA,H,NP)
>            COMPLEX H(NP),XA(NP),DX2A(NP),DX2B(NP)
>            COMMON/VEDATA/AM,BM,TK,SK,C,PI
>            C1 = AM/TK
>            C2 = BM/TK
>            DO 1 I = 1,NP
>      1     H(I) = XA(I) + C1*DX2A(I) + C2*DX2B(I)
>            RETURN
>            END
#END OF FILE
#
```

Appendix 1

```
C     THE VEHICLE PARAMETERS
C     BM = BODY MASS, AM = AXLE MASS, TK = TIRE SPRING
C     RATE, SK = SUSPENSION SPRING RATE, C = DAMPING
C     COEFFICIENT, NP = NUMBER OF DATA POINTS, V = SP
C     EED OF THE VEHICAL, AL = LENGTH OF THE SPAN,
C     (FOR FFT NP=2**N, WHERE N IS AN INTEGER)
C
      COMPLEX H(128), SH(128), SHNEW(128)
      DIMENSION XA(128), XB(128), DX2A(128), DX2B(128)
      DIMENSION HH(128), F(128), PHASEF(128), S1(128)
      DIMENSION S2(128), DPSD(128), Y(4), DERY(4)
      INTEGER RUNGE
      COMMON/FFF/SH,NP
      COMMON/XAB/XA,XB
      COMMON/VEDATA/AM,BM,TK,SK,C,PI
      COMMON/PROFIL/V,AL
      PI = 3.14592653589793
C      READING THE DATA RELATED TO VEHICLE PARAMETERS
      READ(5,203)AM,BM,TK,SK,C
C      READING THE LENGTH OF THE SPAN AL, AND THE VELOCIPT V
      READ(5,204)V,AL,NP
203   FORMAT(5F15.6)
204   FORMAT(2F15.6,I3)
      WRITE(6,101)AM,BM,TK,SK,C
      WRITE(6,102)V,AL,NP
101    FORMAT(1H1//5X,'$$$  VEHICLE SUSPENSION DESIGN  *$$'/
     25X,'********************************************'//
     25X,' INPUT DATA FOR THE SYSTEM :'/
     25X,'   UNSPRUNG MASS              = ',F10.2,'   KG'/
     25X,'   SPRUNG MASS                = ',F10.2,'   KG'/
     25X,'   TIRE SPRING RATE           = ',F10.2,'   N/M'/
     25X,'   SUSPENSION SPRING RATE     = ',F10.2,'   N/M'/
     25X,'DAMPING COEFFICIENT           = ',F10.2,' '/
     25X,'  ----------------------------------------'///
102    FORMAT(5X,'  INPUT DATA:'/
     25X,'   SPEED OF THE VEHICLE = ',F6.2,'   M/SEC'/
     25X,'   TERRAIN WAVE LENGTH: L = ',F7.2,' M '/
     25X,'   NUMBER OF OBSERVATION POINTS = ',I5//
     25X,'  ----------------------------------------'//)
C      SUBROUTINE ROUGH TO HANDLE THE TERRAIN DATA READING
C      IN FREE FORMAT
      CALL ROUGH(NP,SH)
C      SUBROUTINE PSDCAL CALCULATES THE POWER SPECTRAL DENSITY
      CALL PSDCAL(SH,S1,NP)
      N = 7
C      A FAST FOURIER TRANSFORM ALGORITHM, WHERE THE TOTAL NO
```

```
      C        OF POINTS NP IS ALWAYS AN INTEGRAL POWER N OF 2
               CALL FFT(SH,N,NP)
      C         SUBROUTINE FUN COMPUTES THE TERRAIN ROUGHNESS VALUE FROM
      C         THE COMPLEX FOURIER SERIES
               CALL FUN(F)
      C         PHASE SHIFT NEEDED, BECAUSE THE VALUES OBTAINED FROM
      C         THE COMPLEX FOURIER SERIES ARE ADVANCED IN PHASE BY ONE
      C         INCREMENT (BETWEEN TWO OBSERATION POINTS)
               DO 14 I=1,128
      14       PHASEF(I) = F(I)
               DO 15 I=2,128
      15        F(I) = PHASEF(I-1)
               F(1) = PHASEF(128)
      C         4TH ORDER RUNGE-KUTTA INEGRATION STARTS HERE
               T =0.0
               TMAX = AL/V
               DELT = TMAX/128.0
               NDIM = 4
               DO 2 I=1,NDIM
      2        Y(I) = 0.0
      C         RUNGE IS A FUNCTION SUBPROGRAM FOR INTEGRATION
      3        K = RUNGE(4,Y,DERY,T,DELT)
               IF(K.NE.1)GO TO 5
               DERY(1) = Y(3)
               DERY(2) = Y(4)
               CCC = C*(Y(4) - Y(3)) + SK*(Y(2) - Y(1))
      C         THIS PROCEDURE TO OBTAIN AN INTEGER TO BE USED
      C         AS THE SUBSCRIPT OF THE DESCRETE DATA ARRAY WAS NECESSARY
      C         BECAUSE OF HARDWARE LIMITATIONS OF THE COMPUTER
               X = T/DELT
               II = IFIX(X)
               REST = X-II
               IF(REST.GT.0.75)II=II+1
               FF = F(II)
               XNEW = FLOAT(II)
               IF(ABS(X-XNEW).LT.0.1)GO TO 7
               FF = (F(II+1)+F(II))/2.0
               GO TO 6
      7        XA(II) = Y(1)
               XB(II) = Y(2)
               DX2A(II) = (1./AM)*(CCC-TK*(Y(1)-FF))
               DX2B(II) = (1.0/BM)*(-CCC)
      6        DERY(3)=(1.0/AM)*(CCC-TK*(Y(1)-FF))
               DERY(4) = (1.0/BM)*(-CCC)
      5        CONTINUE
               IF (T.LT.TMAX)GO TO 3
      C         SUBROUTINE HCAL COMPUTES THE TERRAIN ROUGHNESS ONCE
      C         BODY AND AXLE ACCLERATIONS , AND THE AXLE  DISPLACEMENT
      C         ARE KNOWN
               CALL HCAL(DX2A,DX2B,XA,HH,NP)
               DO 10 I=1,NP
      10       SHNEW(I) = CMPLX(HH(I),0.0)
      C         SUB ROUTINE PSDCAL IS CALLED TO COMPUTE THE POWER
      C         DENSITY OF  THE CALCULATED TERRAIN ROUGHNESS DATA
               CALL PSDCAL(SHNEW,S2,NP)
```

```
                 WRITE(6,201)
                 DO 1 J=1,NP
                 DPSD(J) = (S1(J) - S2(J))*100.0/S1(J)
         1       WRITE(6,202)S1(J),S2(J),DPSD(J)
         201     FORMAT(1H1///25X,'POWER SPECTRAL DENSITY COMPUTATIONS'///
                116X,'TERRAIN DATA',10X,'COMPUTED DATA',10X,'% DIFFERENCE'//
                2)
         202     FORMAT(5X,3E22.5/)
                 STOP
                 END
*OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
*OPTIONS IN EFFECT*  NAME = MAIN     , LINECNT =       57
*STATISTICS*     SOURCE STATEMENTS =          68,PROGRAM SIZE =       8652
*STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
C
C       *************SUBROUTINE FUN STARTS HERE***********
C        THIS SUBROUTINE IS USED TO COMPUTE THE COMPLEX
C        SERIES SUM
        SUBROUTINE FUN(F)
        DIMENSION F(128)
        COMPLEX A(128),AF(128),CMPLX
         COMMON/FFF/A,NP
        COMMON/VEDATA/AM,BM,TK,SK,C,PI
        COMMON/PROFIL/V,AL
         DO 4 I=1,NP
        F(I) = 0.0
        ANP = FLOAT(NP)
        DO 5 J=1,NP
        NI = I*J
        JJ = NI/NP
        ANI = FLOAT(NI)
C        A LITTLE TRICK TO AVOID HAVING A LARGE ARGUMENT
C        FOR THE SINE AND COSINE FUNCTIONS
        TH = 2.0*PI*((ANI/ANP)-JJ)
        SS = SIN(TH)
        CC = COS(TH)
        AF(I) = AF(I) + A(J)*CMPLX(CC,SS)
5        CONTINUE
        ARF=REAL(AF(I))
        AIF = AIMAG(AF(I))
C        SIGN OF THE RESULTANT FUNCTION VALUE DEPENDS ON THE
C        SIGN OF THE IMAGINARY PART
C        SAME FOR THE FIRST HALF
C        OPPOSITE FOR THE SECOND HALF
        RATI =ARF/AIF
        IF(I.LE.64)GO TO 2
        AIF = -AIF
2       F(I) = AIF*SQRT(1.0+RATI*RATI)
      4 CONTINUE
        RETURN
        END
*OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
*OPTIONS IN EFFECT*  NAME = FUN      , LINECNT =      57
*STATISTICS*     SOURCE STATEMENTS =        27,PROGRAM SIZE =     190-
*STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
      C
      C     **************SUBROUTINE ROUGH STARTS HERE************
      C     THIS IS A SUBROUTINE WRITTEN FOR FREE FORMAT READING
      C     OF THE TERRAIN DATA WHICH USUALLY BE GIVEN IN FEET, BUT
      C     IF THE DATA IS GIVEN IN METERS THEN SEE BELOW FOR A NECESSARY
      C     CHANGE
            SUBROUTINE ROUGH(N,H)
            DIMENSION H1(1024)
            COMPLEX H(N)
            REAL*4 FMT(1)/'*'/
            READ(5,FMT)(H1(I),I=1,N)
            S=0.0
            DO 2 I=1,N
      2     S=S+H1(I)
            HAV = S/FLOAT(N)
            DO 1 I=1,N
            H1(I) = H1(I)-HAV
      C     FOR DATA IN METERS FOLLOWING ONE CARD CONTAINING THE
      C     MULTIPLYING FACTOR SHOULD BE REMOVED
            H1(I) = H1(I)*0.3048
      1     H(I) = CMPLX(H1(I),0.0)
      C     WRITE(6,101) (H(I),I=1,N)
      101   FORMAT(1H1///' TERRAIN ROUGHNESS INPUT :'/
           @2X,' *********************************'///
           @2X,'HEIGHTS W.R.T. A REFRENCE'///
           @(2X,4F12.5/))
            RETURN
            END
*OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
*OPTIONS IN EFFECT*  NAME = ROUGH    , LINECNT =      57
*STATISTICS*     SOURCE STATEMENTS =       16,PROGRAM SIZE =      4562
*STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
C
C     ****************SUBROUTINE PSDCAL STARTS HERE**********
C     THE FORMULA USED HERE CAN BE FOUND IN ANY TEXT ON
C     ON RANDOM VIBRETIONS
      SUBROUTINE PSDCAL(H,S,NP)
      COMPLEX H(NP)
      DIMENSION S(NP)
      COMMON/VEDATA/AM,RM,TK,SK,C,PI
      COMMON/PROFIL/V,AL
      OMEGA = 2.*PI*V/AL
      ETA = OMEGA*SQRT(RM/SK)
      DO 1 I=1,NP
    1 S(I) = H(I)*CONJG(H(I))/(2.*ETA)
      RETURN
      END
*OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
*OPTIONS IN EFFECT*  NAME = PSDCAL   , LINECNT =      57
*STATISTICS*    SOURCE STATEMENTS =        11,PROGRAM SIZE =      648
*STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
      C
      C        ****************SUBROUTINE FFT STARTS HERE*************
               SUBROUTINE FFT(A,N,NB)
               COMPLEX A(NB),U,W,T,CMPLX
      C        DIVIDING ALL ELEMENTS BY NB
               DO 1 J=1,NB
      1        A(J) = A(J)/NB
      C        REORDERING THE SEQUENCE
               NBD2 = NB/2
               NBM1 = NB - 1
                J = 1
               DO 4 L = 1,NBM1
               IF(L.GE.J)GO TO 2
               T = A(J)
               A(J) = A(L)
               A(L) = T
      2        K=NBD2
      C        WRITE(6,101)(A(I),I=1,6)
      101      FORMAT(3F15.6)
      3        IF(K.GE.J)GO TO 4
               J = J - K
               K = K/2
               GO TO 3
      4        J = J+K
      C        COMPUTATION OF FFT
               PI = 3.14159265358979
               DO 6 M=1,N
               U = (1.0,0.0)
               ME = 2**M
               K = ME/2
               W = CMPLX(COS(PI/K), -SIN(PI/K))
               DO 6 J=1,K
               DO 5 L=J,NB,ME
               LPK = L+K
               T = A(LPK)*U
               A(LPK) = A(L) - T
      C        WRITE(6,102)A(LPK)
      102      FORMAT(2F13.5)
      5        A(L) = A(L)+T
      6        U = U*W
               RETURN
               END
*OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
*OPTIONS IN EFFECT*  NAME = FFT      , LINECNT =       57
*STATISTICS*     SOURCE STATEMENTS =        35,PROGRAM SIZE =      [illegible]
*STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
      C
      C       *****************SUBROUTINE HCAL STARTS HERE************
      C        IF WE ADD THE TWO EQUATIONS OF MOTION FOR BODY AND AXLE
      C        THEN WE GET REQUIRED RELATION TO OBTAIN TERRAIN ROUGHNESS
              SUBROUTINE HCAL(DX2A,DX2B,XA,H,NP)
              COMPLEX H(NP),XA(NP),DX2A(NP),DX2B(NP)
              COMMON/VEDATA/AM,BM,TK,SK,C,PI
              C1 = AM/TK
              C2 = BM/TK
              DO 1 I = 1,NP
      1       H(I) = XA(I) + C1*DX2A(I) + C2*DX2B(I)
              RETURN
              END
 *OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
 *OPTIONS IN EFFECT*  NAME = HCAL    , LINECNT =     57
 *STATISTICS*     SOURCE STATEMENTS =         9,PROGRAM SIZE =      572
 *STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
C       ************ SUBPROGRAM FUNCTION RUNGE STARTS HERE********
C        FUNCTION SUBPROGRAM FOR 4TH ORDER RUNGA-KUTTA METHOD
        FUNCTION RUNGE(N,Y,F,X,H)
        INTEGER RUNGE
        DIMENSION PHI(50),SAVEY(50),Y(N),F(N)
        DATA M/0/
        M = M + 1
        GO TO (1,2,3,4,5),M
1       RUNGE=1
        RETURN
2       DO 22 J=1,N
        SAVEY(J) = Y(J)
        PHI(J) = F(J)
22      Y(J) = SAVEY(J) + .5*H*F(J)
        X = X + .5*H
        RUNGE =  1
        RETURN
3       DO 33 J=1,N
        PHI(J) = PHI(J) + 2.*F(J)
33      Y(J) = SAVEY(J)+.5*H*F(J)
        RUNGE=1
        RETURN
4       DO 44 J=1,N
        PHI(J) = PHI(J)+2.*F(J)
44      Y(J) = SAVEY(J) + H*F(J)
        X = X + 0.5*H
        RUNGE = 1
        RETURN
5       DO 55 J=1,N
55      Y(J) = SAVEY(J)+(PHI(J)+F(J))*H/6.
        M = 0
        RUNGE = 0
        RETURN
        END
*OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
*OPTIONS IN EFFECT*  NAME = RUNGE    , LINECNT =       57
*STATISTICS*     SOURCE STATEMENTS =        32,PROGRAM SIZE =      [illegible]
*STATISTICS*  NO DIAGNOSTICS GENERATED

NO STATEMENTS FLAGGED IN THE ABOVE COMPILATIONS.
```

APPENDIX B

Appendix B

Equations for optimal control based on the condition that relative suspension mean deflection is 1/3 of allowable axle clearance H and absolute acceleration transmissibility be a minimum:

for n^{th} harmonic $(j=\sqrt{-1})$

$$m_b\ddot{x}_b+c(\dot{x}_b-\dot{x}_a)+k(x_b-x_a)=0 \qquad a)$$

$$m_a\ddot{x}_a-c(\dot{x}_b-\dot{x}_a)-k(x_b-x_a)+Kx_a=Kh_n\ \exp(j\omega nt) \qquad b)$$

$$x_b-x_a=y \qquad c)$$

Multiply a) by m_a, b) by m_b and subtract b) from a) and divide by m_am_b ;

$$\ddot{y}+c(\ (m_a+m_b)/m_am_b)\dot{y}+k(\ \frac{(m_a+m_b)}{m_am_b})y+y(K/m_a)-x_b(K/m_b)= h_n(K/m_a)\exp(ju\omega t) \qquad d)$$

and from a)

$$\ddot{x}_b+\dot{y}(c/m_b)+y(k/m_b)=0 \qquad e)$$

Let $x_b=x_b\ \exp\ j(n\omega t+\phi)$, $y=Y\ \exp\ j(n\omega t+\psi)$ f)

Then

$$\begin{bmatrix} (-\omega^2n^2+\frac{k+K}{m_a}+\frac{k}{m_b}+c((m_a+m_b)/m_am_b)j\omega n), & -K/m_a \\ (\frac{c}{m_b}\ j\omega n+\frac{k}{m_b}) & \omega^2n^2 \end{bmatrix}\begin{Bmatrix} Y\ \exp\ j\phi \\ X\ \exp\ j\psi \end{Bmatrix}=$$

$$\begin{Bmatrix} Kh_n/m_a \\ 0 \end{Bmatrix} \qquad g)$$

Determinant $\bar{D}$:

$$\omega^4n^4-\omega^2n^2(\frac{k+K}{m_a}+\frac{k}{m_b}+c\ \frac{m_a+m_b}{m_am_b}\ j\omega n)+\frac{K}{m_a}(\frac{c}{m_a}\ j\omega n+\frac{k}{m_b})=\bar{D} \qquad h)$$

$$\exp(j\phi)Y = \frac{-kh_n\omega^2 n^2}{\bar{D}m_a} \qquad \text{i)}$$

$$\exp(j\psi)X = \frac{Kh_n(cj\omega n/m_a + k/m_b)}{\bar{D}\, m_a} \qquad \text{j)}$$

After Rationalizing i), j)

$$\left(\frac{Y_n}{h_n}\right)^2 = \frac{\eta_n^4}{\left[\eta_n^4\,\omega_b^2/\Omega_a^2 - \eta_n^2\left(1+\frac{k}{K}+\frac{\omega_b^2}{\Omega_a^2}\right)+1\right]^2 + 4\zeta^2\eta_n^2\left[\eta_n^2\left(\frac{k}{K}+\frac{\omega_b^2}{\Omega_a^2}\right)-1\right]^2} \qquad \text{k)}$$

$$\left(\frac{X_n}{h_n}\right)^2 = \frac{1+4\zeta^2\eta_n^2}{\left[\eta_n^4\frac{\omega_b^2}{\Omega_a^2} - \eta_n^2\left(1+\frac{k}{K}+\frac{\omega_b^2}{\Omega_a^2}\right)+1\right]^2 + 4\zeta^2\eta_n^2\left[\eta_n^2\left(\frac{k}{K}+\frac{\omega_b^2}{\Omega_a^2}\right)-1\right]^2} \qquad \text{l)}$$

Where in k), l) $\eta = \omega n/\omega_b$, $k/m_b = \omega_b^2$, $K/m_a = \Omega_a^2$,

$\zeta = c/c_c$, $c_c = 2(k\, m_b)^{1/2}$;

Let it be required that

$$\alpha\,\bar{y} \leq H \quad \text{ot} \quad \bar{y} = H/\alpha = H/3 \quad (\alpha=3) \qquad \text{m)}$$

$$\bar{y}^2 = \frac{H^2}{9} = \frac{1}{2m}\sum_1^m h_n^2\,(X/h_n)^2 = \frac{1}{2m}\sum_1^m Y^2 \qquad \text{n)}$$

$$\bar{x}^2 = (1+4\zeta^2\bar{y}^2)\,\bar{\eta}^4 \qquad \bar{\eta}^2 = \text{mean square value of } \eta_n^2 \qquad \text{o)}$$

$$\bar{\eta}^2 = \bar{\omega}^2/\omega_b^2 = \frac{4\pi\bar{u}^2}{\ell^2\omega_b^2} \qquad \bar{u}^2 = \text{mean square value of speed } u \qquad \text{p)}$$

The program for n) and o) follows.

```
              C      THE VEHICLE PARAMETERS
              C      BM = BODY MASS, AM = AXLE MASS, TK = TIRE SPRING
              C      RATE, SK = SUSPENSION SPRING RATE, C = DAMPING
              C      COEFFICIENT, NP = NUMBER OF DATA POINTS, V = SP
              C
              C      (FOR FFT [illegible]N, WHERE N IS AN INTEGER)
              C
              C
0001                  IMPLICIT REAL *8(A-H,O-Z)
0002                 COMPLEX *16 [illegible](128), SH(128), SHNEW(128)
0003                 INTEGER [illegible]
              C
0004                  DIMENSION ROOT(2), WA(15)
0005                 DIMENSION [illegible](128),A(128),XB(128),DX2A(128),DX2B(128)
0006                 DIMENSION Y(4),DERY(4),PRMT(5),AUX(16,4)
0007                   DIMENSION [illegible](128)
0008                 DIMENSION [illegible](128)
0009                 DIMENSION [illegible](128),PHASEF(128)
0010                 COMMON/[illegible]/NP
0011                 COMMON/[illegible]
0012                 COMPLEX *16 SSH(129),DIFH(128)
0013                 DIMENSION S1(128), S2(129), DPSD(128)
0014                 COMMON/VEDATA/AM,BM,TK,SK,C,PI
0015                 COMMON/PROPTY/V,AL
0016                 COMMON/[illegible]
0017                 INTEGER [illegible]
0018                 PI = 3.14592653589793
0019                 READ(5,203)AM,BM,TK,SK,C
0020                 READ(5,[illegible]AL,HCLEAR,NP
0021          203    FORMAT([illegible])
0022          204    FORMAT([illegible],I3)
              C      WRITE(6,[illegible]BM,TK,SK,C
              C      WRITE(6,[illegible]V,AL,NP
0023          101    FORMAT([illegible]//5X,'SSS  VEHICLE SUSPENSION DESIGN  SSS'/
                    @5X,'****************************************'//
                    @5X,' INPUT DATA FOR THE SYSTEM :'/
                    @5X,'  UNSPRUNG MASS                = ',F10.2,'  KG'/
                    @5X,'  SPRUNG MASS                  = ',F10.2,'  KG'/
                    @5X,'  TIRE SPRING RATE             = ',F10.2,'  N/M'/
                    @5X,'  SUSPENSION SPRING RATE       = ',F10.2,'  N/M'/
                    @5X,'DAMPING COEFFICIENT            = ',F10.2,' '/
                    @5X,' -------------------------------------------'///)
0024          102    FORMAT(5X,' INPUT DATA:'/
                    @5X,'  SPEED OF THE VEHICLE = ',F6.2,'  M/SEC'/
                    @5X,'  TERRAIN WAVE LENGTH: L = ',F7.2,' M '/
                    @5X,'  NUMBER OF OBSERVATION POINTS = ',I5//
                    @5X,' -------------------------------------------'///)
0025                 U = 20.0
              C
0026                 CALL ROUGH(NP,SH)
0027                 DO 12 I=1,128
0028          12     SSH(I) = SH(I)
              C      DO 500 IU=1,10
0029                 N = 7
0030                 CALL FFT(SH,N,NP)
```

```
C
      CALL OPTIM(AM,BM,TK,PI,AL,U,SH,NP)
      CALL PSDCAL(SH,SI,NP)
      CALL FUN(F)
      DO 14 I=1,128
   14 PHASEF(I) = F(I)
      DO 15 I=2,128
   15 F(I) = PHASEF(I-1)
      F(1) = -PHASEF(128)
      T =0.0
C
C
      TMAX = AL/V
      DELT = TMAX/128.0
      NDIM = 4
C
C
      DO 2 I=1,NDIM
    2 Y(I) = 0.0
    3 K = RUNGE(4,Y,DERY,T,DELT)
      IF(K.NE.1)GO TO 5
      DERY(1) = Y(3)
      DERY(2) = Y(4)
      CCC = C*(Y(4) - Y(3)) + SK*(Y(2) - Y(1))
      X = T/DELT
      II = IFIX(SNGL(X))
      RESD = X-II
      IF(RESD.GT.0.75)II=II+1
      FF = F(II)
      XNEW =II
      IF(DABS(X-XNEW).LT.0.1)GO TO 7
      FF = (F(II+1)+F(II))/2.0
      GO TO 6
    7 XA(II) = Y(1)
      XB(II) = Y(2)
      DX2A(II) = (1./AM)*(CCC-TK*(Y(1)-FF))
      DX2B(II) = (1.0/BM)*(-CCC)
    6 DERY(3)=(1.0/AM)*(CCC-TK*(Y(1)-FF))
      DERY(4) = (1.0/BM)*(-CCC)
C
C
    5 CONTINUE
      IF (T.LT.TMAX)GO TO 3
C
C     CONSTRAINT EQUATION FOR OPTIMIZATION
C
C
  301    FORMAT('ROOTS ARE', 2E17.7)
C
      CALL HCAL(DX2A,DX2B,XA,HH,NP)
      DO 18 I=1,128
   18 ORIGH(I) = REAL(SSH(I))
      DO 10 I=1,NP
   10 SHNEW(I) = DCMPLX(HH(I),0.002)
      CALL FFT(SHNEW,N,NP)
```

```
                 CALL PSDCAL(SHNEW,S2,NP)
                 WRITE(6,201)
                 DO 1 J=1,NP
                 DPSD(J)=(ORIGH(J)-HH(J))*100.0/ORIGH(J)
         1       WRITE(6,202)ORIGH(J),HH(J),DPSD(J)
         201     FORMAT(1H1///,'     COMPARISION BETWEEN ORIGINAL & COMPUTED DAT
                @5X,'TERRAIN DATA',10X,'COMPUTED DATA',10X,'% DIFFERENCE'//
                @)
         202     FORMAT(5X,3E22.5/)
                 WRITE(6,206)
         206     FORMAT(1H1,'           LOGRITHMIC OUTPUT'/
                @5X,'FREQUENCY',8X,'PSD',14X,'LOG(FRQ)',9X,'LOG(PSD)')
                 OMEGA = 2.0*PI*V/AL
                 ETA = OMEGA*DSQRT(BM/SK)
         C        TAKING LOGRITHMS OF PSD AND FREQUENCY VALUES
                 DO 16 I=1,NP
                 PSD=S1(I)*ETA*AL/(2.0*PI)
                 FRQ = I*2.0*PI/AL
                 PSDL=DLOG10(PSD)
                 FRQL = DLOG10(FRQ)
                 IF((I.EQ.1).OR.(I.GT.65))GO TO 16
                 WRITE(6,210)FRQ,PSD,FRQL,PSDL
         16      CONTINUE
         210        FORMAT(5X,4E17.6)
         C
         99       CONTINUE
                 STOP
                 END
 *OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
 *OPTIONS IN EFFECT*  NAME = MAIN    , LINECNT =      57
 *STATISTICS*     SOURCE STATEMENTS =          96,PROGRAM SIZE =     22542
 *STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
C
C     SUBROUTINE OPTIM STARTS HERE
C
      SUBROUTINE OPTIM(AM,BM,TK,PI,AL,U,SH,NP)
      IMPLICIT REAL *8(A-H,O-Z)
C
      DIMENSION ROOT(9), V(9)
      DIMENSION COE(9), RR(9), RC(9), POL(9)
      COMPLEX *16   CONSH, SH(128)
C
C     WRITE(6,411)U
411   FORMAT(' U =',D17.6)
C     WRITE(6,401)(SH(I),I=125,128)
      SIGMAH = 0.0
C     WRITE(6,402)NP
402   FORMAT('    NP =',I5)
      DO 10 N=1,NP
10     SIGMAH = SIGMAH + CDABS(SH(N))
C
C     WRITE(6,407)SIGMAH
407   FORMAT('SIGMAH =',D17.6)
C
      DO 40 IH = 15, 40, 3
      XSQMIN = 1.0D15
      H = IH*0.01
      ANP = NP
      CC = 9.0*SIGMAH/(ANP*H*H)
      WRITE(6,408)CC
408   FORMAT('CC =',D17.6)
      DO 30 IZ = 1,10
      Z = 0.1*IZ
      WRITE(6,421)
421   FORMAT(' ENTERED FIRST DO LOOP')
      DO 30 IK= 1,10
      SK = 1000.0*IK
      OMB = DSQRT(SK/BM)
      OMA = DSQRT(TK/AM)
      OMR = OMB/OMA
      WRITE(6,422)
422   FORMAT('  ENTERED THE SECOND LOOP')
      SKR = SK/TK
      C11 = SKR + OMR*OMR
      C12 = C11 + 1.0
      Z2 = Z*Z
      COE(1) = CC
      COE(2) = 0.0
      COE(3) = 4.*Z2 - 2.*C12
      COE(4) = 0.0
      COE(5) = C12*C12 + 2.*OMR*OMR - CC - 8.*Z2*C11*C11
      COE(6) = 0.0
      COE(7) = 4.*Z2*C11*C11 - 2.*OMR*OMR*C12
      COE(8) = 0.0
      COE(9) = OMR**4
C
C
```

```
 403   FORMAT('CCE   ',D17.6)
C      CALLING A PROGRAM FROM SSP
C
       CALL DPRBM(COE,9,RR,RC,POL,IR,IER)
C
C
 404   FORMAT('RRE RC',D17.6)
C      WRITE(6,405)IR
 405   FORMAT('IR =',I5)
       IF(IR.EQ.0)GO TO 30
       I = 0
       J=1
 19     IF(RC(J).EQ.0.001)GO TO 20
       IF(J.EQ.IR)GO TO 25
       J = J+1
       GO TO 19
 20     IF(RR(J).GE.0.001)GO TO 22
       IF(J.EQ.IR)GO TO 25
       J = J +1
       GO TO 19
 22    I = I + 1
       ROOT(I) = RR(J)
       J = J + 1
       GO TO 19
 25     CONTINUE
       IF(I.EQ.0)GO TO 30
C       WRITE(6,201)((J,ROOT(J)),J=1,I)
 201   FORMAT(' ROOT(',I1,') = ',D17.6)
       DO 27 J = 1,I
 27     V(J) = 0.5*ROOT(J)*AL*OMB/PI
       DO 29 J1=1,I
       IF(DABS(U-V(J1)).GT.0.2)GO TO 29
       DO 28 J = 1, I
       ROO2 = ROOT(J)*ROOT(J)
       ROO4 = ROO2*ROO2
       XSQ = (1.+4.*Z2*ROO2)/(ROO4*CC)
       IF(XSQ.GE.XSQMIN)GO TO 28
       XSQMIN = XSQ
       SKOPT = SK
       ZOPT = Z
 28     CONTINUE
       WRITE(6,202)((J,V(J)),J=1,I)
 202   FORMAT('    V(',I1,') =',D17.6)
       WRITE(6,203)SK,Z,H
 203   FORMAT('  SK =',D17.6,'  Z =',D17.6,'  H =',F6.2)
 29      CONTINUE
 30     CONTINUE
       WRITE(6,418)SKOPT,ZOPT
 418   FORMAT('SKOPT=',D17.6,'   ZOPT=',D17.6)
 40      CONTINUE
       RETURN
       END
*OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
*OPTIONS IN EFFECT*  NAME = OPTIM   , LINECNT =        57
*STATISTICS*    SOURCE STATEMENTS =       88,PROGRAM SIZE =      2948
```

```
C
C     **************FUN
      SUBROUTINE FUN(F)
      DIMENSION F(128)
      COMPLEX A(128),AF(128),CMPLX
       COMMON/FFF/A,NP
      COMMON/VEDATA/AM,BM,TK,SK,C,FI
      COMMON/PROFIL/X,AL
       DO 4 I=1,NP
      F(I) = 0.0
      ANP = FLOAT(NP)
      DO 5 J=1,NP
      NI = I*J
      JJ = NI/NP
      ANI = FLOAT(NI)
      TH = 2.0*PI*((ANI/ANP)-JJ)
      SS = SIN(TH)
      CC = COS(TH)
      AF(I) = AF(I) + A(J)*CMPLX(CC,SS)
    5  CONTINUE
      ARF=REAL(AF(I))
      AIF = AIMAG(AF(I))
      RATI =ARF/AIF
      IF(I.LE.64)GO TO 2
      AIF = -AIF
    2 F(I) = AIF*SQRT(1.0+RATI*RATI)
    4 CONTINUE
      RETURN
      END
*OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
*OPTIONS IN EFFECT*  NAME = FUN     , LINECNT =       57
*STATISTICS*   SOURCE STATEMENTS =      27,PROGRAM SIZE =      1904
*STATISTICS*  NO DIAGNOSTICS GENERATED
```

MAIN

```
      C
      C       SUBROUTINE ROUGH STARTS
0001            SUBROUTINE ROUGH(N,H)
0002          DIMENSION H1(1024)
0003          COMPLEX H(N)
0004          REAL*4 FMT(1)/'*'/
0005          READ(5,FMT)(H1(I),I=1,N)
0006          S=0.0
0007          DO 2 I=1,N
0008  2       S=S+H1(I)
0009          HAV = S/FLOAT(N)
0010          DO 1 I=1,N
0011          H1(I) = H1(I)-HAV
0012          H1(I) = H1(I)*0.3048
0013  1       H(I) = CMPLX(H1(I),0.0)
      C       WRITE(5,101) (H(I),I=1,N)
0014  101     FORMAT(1H1///' TERRAIN ROUGHNESS INPUT :'/
             22X,'**********************************'///
             22X,'HEIGHTS W.R.T. A REFRENCE'///
             3(2X,4F12.5/))
0015          RETURN
0016          END
 *OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
 *OPTIONS IN EFFECT*  NAME = ROUGH    , LINECNT =        57
 *STATISTICS*    SOURCE STATEMENTS =        16,PROGRAM SIZE =      4562
 *STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
      C
      C        SUBROUTINE PSDCAL
               SUBROUTINE PSDCAL(H,S,NP)
               COMPLEX H(NP)
               DIMENSION S(NP)
               COMMON/VEDATA/AM,BM,TK,SK,C,PI
               COMMON/PROFIL/V,AL
               OMEGA = 2.*PI*V/AL
               ETA = OMEGA*SQRT(BM/SK)
               DO 1 I=1,NP
             1 S(I) = H(I)*CONJG(H(I))/(2.*ETA)
               RETURN
               END
 *OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
 *OPTIONS IN EFFECT*  NAME = PSDCAL  , LINECNT =      57
 *STATISTICS*     SOURCE STATEMENTS =       11,PROGRAM SIZE =        548
 *STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
        C
        C     SUBROUTINE FFT
              SUBROUTINE FFT(A,N,NB)
              COMPLEX A(NB),U,W,T,CMPLX
        C     DIVIDING ALL ELEMENTS BY NB
              DO 1 J=1,NB
        1     A(J) = A(J)/NB
        C     REORDERING THE SEQUENCE
              NBD2 = NB/2
              NBM1 = NB - 1
              J = 1
              DO 4 L = 1,NBM1
              IF(L.GE.J)GO TO 2
              T = A(J)
              A(J) = A(L)
              A(L) = T
        2     K=NBD2
        C     WRITE(6,101)(A(I),I=1,6)
        101   FORMAT(3F15.6)
        3     IF(K.GE.J)GO TO 4
              J = J - K
              K = K/2
              GO TO 3
        4     J = J+K
        C     COMPUTATION OF FFT
              PI = 3.14592653589793
              DO 6 M=1,N
              U = (1.0,0.0)
              ME = 2**M
              K = ME/2
              W = CMPLX(COS(PI/K), -SIN(PI/K))
              DO 6 J=1,K
              DO 5 L=J,NB,ME
              LPK = L+K
              T = A(LPK)*U
              A(LPK) = A(L) - T
        C     WRITE(6,102)A(LPK)
        102   FORMAT(2F13.5)
        5     A(L) = A(L)+T
        6     U = U*W
              RETURN
              END
 *OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
 *OPTIONS IN EFFECT*  NAME = FFT     , LINECNT =        57
 *STATISTICS*     SOURCE STATEMENTS =        35,PROGRAM SIZE =       130[illegible]
 *STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
      C
      C     SUBROUTINE HCAL(DX2A,DX2B,XA,H,NP)
            SUBROUTINE HCAL(DX2A,DX2B,XA,H,NP)
            COMPLEX H(NP),XA(NP),DX2A(NP),DX2B(NP)
            COMMON/VEDATA/AM,BM,TK,SK,C,PI
            C1 = AM/TK
            C2 = BM/TK
            DO 1 I = 1,NP
      1     H(I) = XA(I) + C1*DX2A(I) + C2*DX2B(I)
            RETURN
            END
 *OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
 *OPTIONS IN EFFECT*  NAME = HCAL    , LINECNT =     57
 *STATISTICS*    SOURCE STATEMENTS =      9,PROGRAM SIZE =     672
 *STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
MICHIGAN TERMINAL SYSTEM FORTRAN G(41336)                    MAIN

      C      FUNCTION SUBPROGRAM FOR 4TH ORDER RUNGE-KUTTA METHOD
             FUNCTION RUNGE(N,Y,F,X,H)
             INTEGER RUNGE
             DIMENSION PHI(50),SAVEY(50),Y(N),F(N)
             DATA M/0/
             M = M + 1
             GO TO (1,2,3,4,5),M
      1      RUNGE=1
             RETURN
      2      DO 22 J=1,N
             SAVEY(J) = Y(J)
             PHI(J) = F(J)
      22     Y(J) = SAVEY(J) + .5*H*F(J)
             X = X + .5*H
             RUNGE =  1
             RETURN
      3      DO 33 J=1,N
             PHI(J) = PHI(J) + 2.*F(J)
      33     Y(J) = SAVEY(J)+.5*H*F(J)
             RUNGE=1
             RETURN
      4      DO 44 J=1,N
             PHI(J) = PHI(J)+2.*F(J)
      44     Y(J) = SAVEY(J) + H*F(J)
             X = X + 0.5*H
             RUNGE = 1
             RETURN
      5      DO 55 J=1,N
      55     Y(J) = SAVEY(J)+(PHI(J)+F(J))*H/6.
             M = 0
             RUNGE = 0
             RETURN
             END
  *OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
  *OPTIONS IN EFFECT*  NAME = RUNGE    , LINECNT =        57
  *STATISTICS*    SOURCE STATEMENTS =        32,PROGRAM SIZE =      1416
  *STATISTICS*  NO DIAGNOSTICS GENERATED

NO STATEMENTS FLAGGED IN THE ABOVE COMPILATIONS.
```

APPENDIX C

Appendix C

The algebraic formulation of the problem is given next.

$$\rho\, \bar{\bar{x}}_b = \rho \left(\sum_{n=1}^{n=\infty} \bar{h}_n^2 \;|M_{xb}^n|^2\right)^{1/2} \qquad (3)$$

$$\alpha \bar{y} = \alpha \left(\sum_{n=1}^{n=\infty} \bar{h}_n^2 \;|M_y^n|^2\right)^{1/2} \qquad (4)$$

where $\bar{h}_n^2 = h_n . h_n^*/2$ (5)

h_n^* is the complex conjugate of h_n the amplitude of the n^{th} order harmonic component of the terrain elevation spectrum h_n .

$$|M_{x_b}^n|^2 = \frac{N_1}{D_1} \qquad (6)$$

where

$$N_1 = K^2(\omega^2 c^2 n^2 + k^2) \qquad (7)$$

$$D_1 = [k(1-(n\omega/\omega_o)^2(m_a n^2\omega^2 - (k+K)) + k^2]^2 + (\omega cn)^2 [m_a(n\omega)^2 - K + k(n\omega/\omega_o)^2]^2 \qquad (8)$$

$$|M_y^n|^2 = \frac{N_2}{D_2} \qquad (9)$$

where

$$N_2 = 1 \qquad (10)$$

$$D_2 = [(\omega_o/n\omega)^2 - 1 + (n\omega)^2 m_a (1-\omega_o/n\omega)^2)/K - (k/K)]^2 + (\omega cn)^2 [(\omega_o/n\omega)^2 - (m_a\omega_o^2 + k)/K]^2/k^2 \qquad (11)$$

We use the following nomenclature:

[illegible]: circular frequency of sprung mass when standing (constant) rad/sec

[illegible]/L: impressed circular frequency rad/sec

K: unsprung mass spring rate; N/m

k: sprung mass spring rate; N/m

c: damping constant of shock absorber (average) Nsec/m

M_a. axle mass per wheel set; kg

n: integer 1,2,3,..... order of vibration

$$B_{x2}=n^4\omega^4(c/\omega_o)^2 \qquad (24)$$

$$A_{y1}=[(\omega_o/n\omega)^2-1+(n\omega)^2.(1-(\omega_o/n\omega)^2)m_a/K-(k/K)] \qquad (25)$$

$$A_{y2}=(\omega_o/n\omega)^2-(m_a\omega_o^2+k)/K \qquad (26)$$

$$B_{y1}=1/K \qquad (27)$$

$$B_{y2}=(\omega cn/k)^2(A_{y2}/k+1/K) \qquad (28)$$

Substitution of (14) to (28) into (12) and (13),respectively, will yield two simultaneous algebraic equations in the unknown parameters k and c. Note that because of automatic height control with ω_o equal a constant the pro-rated mass m_b does not enter into the equations explicitly but is contained in ω_o.

For the terrain identification (subroutine) we write:

$$\phi^n_{xx} = \bar{h}_n{}^2/\Omega_n = \bar{h}_n^2\, u/\omega_n=\phi_t.u \qquad (29)$$

where in (29) ϕ^n_{xx} is the n^{th} order power spectral density value (m^3/rad), Ω_n in the wave number of the n^{th} order wave (Rad/m), ω_n is the n^{th}order circular frequency (rad/sec) and $\phi^n_t=\bar{h}_n{}^2/\omega_n$ (m^2sec/rad) is the n^{th} order power spectral density value relative to time. So

$$\phi^n_{xx} = u\phi^n_t \qquad (30)$$

also

$$\phi_t = Au\;{}^2 \text{ (approximately)} \qquad (31)$$

and

$$\phi_t = \bar{h}_n^2/\omega \qquad (32)$$

such that

$$\bar{h}_n^2 = Au/\omega = A/\Omega = \phi_{xx}.\Omega \qquad (33)$$

The average A- value A_{avg} is then

Partial differentiating (1) makes P a minimum, if

$$\frac{\partial P}{\partial k} = \rho \frac{\partial \bar{\bar{x}}_b}{\partial k} + \alpha \frac{\partial \bar{y}}{\partial k} = 0 \tag{12}$$

$$\frac{\partial P}{\partial c} = \rho \frac{\partial \bar{\bar{x}}_b}{\partial c} + \alpha \frac{\partial \bar{y}}{\partial c} = 0 \tag{13}$$

where

$$\frac{\partial \bar{\bar{x}}_b}{\partial k} = \left(\sum_{n=1}^{n=\infty} \bar{h}_n^2 |M_{x_b}^n|^2\right)^{-1/2} \cdot \sum_{n=1}^{n=\infty} \bar{h}_n^2 \, n^4 \frac{\partial |M_{xb}^n|^2}{\partial k} \tag{14}$$

$$\frac{\partial \bar{y}}{\partial k} = \left(\sum_{n=1}^{n=\infty} \bar{h}_n^2 |M_{xb}^n|^2\right)^{-1/2} \cdot \sum_{n=1}^{n=\infty} \bar{h}_n^2 \frac{\partial |M_y^n|^2}{\partial k} \tag{15}$$

$$\frac{\partial \bar{\bar{x}}_b}{\partial c} = \left(\sum_{n=1}^{n=\infty} \bar{h}_n^2 |M_{xb}^n|^2\right)^{-1/2} \cdot \sum_{n=1}^{n=\infty} \bar{h}_n^2 \frac{\partial |M_{xb}^n|^2}{\partial c} \tag{16}$$

$$\frac{\partial \bar{y}}{\partial c} = \left(\sum_{n=1}^{n=\infty} \bar{h}_n^2 |M_y|^2\right)^{-1/2} \cdot \sum_{n=1}^{n=\infty} \bar{h}_n^2 \frac{\partial |M_y^n|^2}{\partial c} \tag{17}$$

$$\frac{\partial |M_{xb}^n|^2}{\partial k} = 2[D_1 kK - N(A_{x1} B_{x2})]/D_1^2 \tag{18}$$

$$\frac{\partial |M_{xb}^n|^2}{\partial c} = 2\, cn^2 \omega^2 \cdot [D_1 K^2 - N_1 A_{x2}^2]/D_1^2 \tag{19}$$

$$\frac{\partial |M_y^n|^2}{\partial k} = -2[A_{y1} B_{y1} + A_{y2} B_{y2}]/D_2^2 \tag{20}$$

$$\frac{\partial |M_y^n|^2}{\partial c} = 2c\omega^2 n^2 A_{y2}^2/k^2 \tag{21}$$

and

$$A_{x1} = k(1-(n\omega/\omega_o)^2)(m_a n^2 \omega^2 - (k+K)) + k^2 \tag{22}$$

$$A_{x2} = (m_a n^2 \omega^2 - K + k(n\omega/\omega_o)^2)$$

$$B_{x1} = (1-(n\omega/\omega_o)^2)(K + m_a n^2 \omega^2)(K + m_a n^2 \omega^2) + 2k(n\omega/\omega_o)^2 \tag{23}$$

$$A_{avg} = (\sum_{n=1}^{n=100} \phi_{xx}\,\Omega_n^2)/100 \qquad (34)$$

Equations (1) through (34) are processed and the program is shown next.

(II b)

```
      C     AM = BODY MASS, BM = AXLE MASS, TK = TIRE SPRING
      C     RATE, SK = SUSPENSION SPRING RATE, C = DAMPING
      C     COEFFICIENT, NP = NUMBER OF DATA POINTS, V = SP
      C     EED OF THE VEHICAL, AL = LENGTH OF THE SPAN,
      C     (FOR FFT NP=2**N, WHERE N IS AN INTEGER)
      C
      C
            IMPLICIT REAL *8(A-H,O-Z)
            COMPLEX *16 H(128), SH(128), SHNEW(128)
            INTEGER RUNGE
             DIMENSION ROOT(2), WA(15)
            DIMENSION CCCCC(2,3)
            DIMENSION XA(128),A(128),XB(128),DX2A(128),DX2B(128)
            DIMENSION Y(4),DERY(4),PRMT(5),AUX(16,4)
             DIMENSION HH(128)
            DIMENSION ORIGH(128)
            DIMENSION F(128),PHASEF(128)
            COMMON/FFF/SH,NP
            COMMON/XAB/XA,XB
            COMPLEX *16 SSH(128),DIFH(128)
            DIMENSION S1(128), S2(128), DPSD(128)
            COMMON/VEDATA/AM,BM,TK,SK,C,PI
            COMMON/PROFIL/V,AL
            COMMON/HCHH/HCH
            INTEGER RUNGE
            PI = 3.14159265358979
            READ(5,203)AM,BM,TK,SK,C
            READ(5,204)V,AL,HCLEAR,NP
        203 FORMAT(5F10.6)
        204 FORMAT(3F10.6,I3)
            WRITE(6,101)AM,BM,TK,SK,C
            WRITE(6,102)V,AL,NP
        101 FORMAT(1H1//5X,'*** VEHICLE SUSPENSION DESIG    ***'/
           ,' ****************************************'/
           ,' INPUT DATA FOR THE SYSTEM :'/
           ,'   SPRUNG MASS                 = ',F10.     '
           ,'   UNSPRUNG MASS               = ',F10.     '
           ,'   TIRE SPRING RATE            = ',F10.     '
           ,'   SUSPENSION SPRING RATE      = ',F10.2,'
           ,'   DAMPING COEFFICIENT         = ',F10.3,' '/
           ,' ----------------------------------------'/
           ,' INPUT DATA:'/
           ,'   SPEED OF THE VEHICLE = ',F8.2,'   /SEC'
           ,'   TERRAIN WAVE LENGTH: L = ',F7.2, ' '
           ,'   NUMBER OF OBSERVATION POINTS = ',I5//
           ,' ----------------------------------------'//
            CALL     (NP,SH)
            DO 12 I=1,128
         12 SSH(I) = SH(I)
      C
            U = 4.0
            N = 7
            CALL FFT(SH,N,NP)
      C
```

(Please print — better copy unavailable G.J.)

```
C     WRITE(6,300)(SH(I),I=1,10)
300   FORMAT('SH IN MAIN',2F17.5)
      READ(5,215)((CCCCC(J,I),J=1,2),I=1,3)
215   FORMAT(2F17.4)
      RCH = 10.0
C
C     WRITE(6,310)ROH
310   FORMAT('ROH = ',E20.7)
C
C
      ITMAX = 100
      EPS = 1.0D-4
      CALL ROOTS1(ROOT,CCCCC)
      WRITE(6,301)ROOT
C
      SK = ROOT(1)
      C = ROOT(2)
      CALL PSDCAL(SH,SI,NP)
      CALL FUN(F)
      DO 14 I=1,128
14    PHASEF(I) = F(I)
      DO 15 I=2,128
15    F(I) = PHASEF(I-1)
      F(1) = -PHASEF(128)
      T =0.0
C
C
      TMAX = AL/V
      DELT = TMAX/128.0
      NDIM = 4
C
C
      DO 5 I=1,NDIM
5     Y(I) = 0.0
7     K = RUNGE(4,Y,DERY,T,DELT)
      IF(K.NE.1)GO TO 5
      DERY(1) = Y(3)
      DERY(2) = Y(4)
      CCC = C*(Y(4) - Y(3)) + SK*(Y(2) - Y(1))
      X = T/DELT
      II = IFIX(SNGL(X))
      FRAC = X-II
      IF(FRAC.GT.0.75)II=II+1
      FF = F(II)
      XNEW =II
      IF(DABS(X-XNEW).LT.0.1)GO TO 7
      FF = (F(II+1)+F(II))/2.0
      GO TO 6
      X2(II) = Y(1)
      X3(II) = Y(2)
      DX2A(II) = (1./AM)*(CCC-TK*(Y(1)-FF))
      DX2B(II) = (1.0/BM)*(-CCC)
6     DERY(3)=(1.0/AM)*(CCC-TK*(Y(1)-FF))
      DERY(4) = (1.0/BM)*(-CCC)
C
```

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```
      C
            [illegible](*,311)Y,DIFY
      311   FORMAT(2E17.6)
      9     CONTINUE
            IF (I.LT.IMAX)GO TO 3
      C
      C     CONSTRAINT EQUATION FOR OPTIMIZATION
      C
      C
            YBAR = 0.0
      C     WRITE(6,305)YBAR
      305   FORMAT('YBAR',E20.7)
            DO 20 J1=1,128
      C     WRITE(6,305)YBAR
      20     YBAR = YBAR + (XB(J1)  - XA(J1))**2
            YBAR = CSQRT(YBAR/128.0)
            ALPHA = 3.0
            HCALC = ALPHA*YBAR
            WRITE(6,335)HCLEAR,HCALC
      335   FORMAT('HHHH =',2E17.6)
            IF(HCLEAR.GE.(ALPHA*YBAR))GO TO 22
            YBAR = 0.0
      [illegible]    CONTINUE
      22      WRITE(6,301)ROOT
      301       FORMAT('ROOTS ARE', 2E17.7)
      C
            [illegible](DX2A,DX2B,XA,HH,NP)
            DO [illegible] I=1,128
      [illegible]   [illegible](I) = REAL(SSH(I))
            DO 10 I=1,NP
      10    SHNEW(I) = DCMPLX(HH(I),0.0D1)
            CALL FFT(SHNEW,N,NP)
            CALL PSCAL(SHNEW,S2,NP)
            WRITE(6,201)
            [illegible] J=1,NP
            [illegible]=(([illegible](J)-HH(J))*100.0/[illegible](J))
            [illegible](J),HH(J),[illegible](J)
            [illegible]//,'     COMPARISION BETWEEN [illegible]
            [illegible] DATA',10X,'COMPUTED DATA',10X,'[illegible]
            [illegible],E20.5/)
            [illegible]
            [illegible]      LOGARITHMIC OUTPUT'/
            [illegible]FREQUENCY',6X,'PSD',14X,'LOG(FREQ)',[illegible]
            OMEGA = 2.0*PI*V/AL
            [illegible] = OMEGA*DSQRT(BM/SK)
            [illegible] LOGARITHMS OF PSD AND FREQUENCY VALUES
            DO [illegible] I=1,NP
            PSD=S2(I)*ETA*AL/(2.0*PI)
            FRQ = I*2.0*PI/AL
            PSDL=DLOG10(PSD)
            FRQL = DLOG10(FRQ)
            IF((I.EQ.1).OR.(I.GT.65))GO TO 16
            WRITE(6,210)FRQ,PSD,FRQL,PSDL
      16    CONTINUE
```

(Please Print better copy unavailable)
G. S.

```
       21      FORMAT(5X,4E17.6)
       9?      CONTINUE
               STOP
               END
*OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
*OPTIONS IN EFFECT*  NAME = MAIN     , LINECNT =       57
*STATISTICS*     SOURCE STATEMENTS =        121,PROGRAM SIZE =     23170
*STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
C     SUBROUTINE SOLVE A SYSTEM OF NONLINEAR EQUATIONS
C     USING A METHOD WHICH DOES NOT NEED THE DERIVATIVE CALCU[illegible]
      SUBROUTINE ROOTS1(X,C)
      IMPLICIT REAL *8(A-H,O-Z)
      DIMENSION B(3,3),C(2,3),X(2),SE(2),E(3),LV(3),MV(3)
      DIMENSION B1(3,3)
      EMIN = 1.0E-7
      N = 2
      NP1 = N + 1
C
110   FORMAT(2E17.7)
C
      DO 3 I = 1,NP1
      B(1,I) = 1.0
      DO 2 J = 1,N
2     X(J) = C(J,I)
      CALL ERR(X,SE)
      DO 11 J=2,NP1
11     B(J,I) = SE(J - 1)
3     CONTINUE
C
51    DO 31 I =1,NP1
      DO 31 J =1,NP1
31    B1(I,J) = B(I,J)
      CALL MINV(B1,NP1,D,LV,MV)
      IF(D.EQ.0.0)GO TO 22
C
      DO 4 J=1,N
      X(J) = 0.0
      DO 4 I = 1,NP1
4     X(J) = X(J) + C(J,I)*B1(I,1)
      CALL ERR(X,SE)
      EE = 0.0
      DO 5 I=1,N
5     EE = EE+SE(I)*SE(I)
      EE = DSQRT(EE)
C
      IF(EE.LE.EMIN)GO TO 21
      WRITE(6,203)EE,X
203   FORMAT(2X,3E17.6)
      L = 1
      DO 7 I = 1,NP1
      E(I) = 0.0
      DO 6 J = 2,NP1
6     E(I) = E(I) + B(J,I)*B(J,I)
      E(I) = DSQRT(E(I))
      IF(I.EQ.1)GO TO 7
      IF(E(I).GT.E(I-1))L=I
7     CONTINUE
      DO 8 I=1,N
      B(I+1,L) = SE(I)
8     C(I,L) = X(I)
      GO TO 51
21      WRITE(6,201) X
201   FORMAT(2E17.6)
```

(Please Print better copy unavailable G. S.)

```
            [illegible]
     22     WRITE(6,102)
    102     FORMAT('  MATRIX B IS SINGULAR')
     23     CONTINUE
            RETURN
            END
*OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
*OPTIONS IN EFFECT*  NAME = ROOTS1   , LINECNT =       57
*STATISTICS*    SOURCE STATEMENTS =        54,PROGRAM SIZE =      1796
*STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
C     **********************SUBROUTINE ERR
      SUBROUTINE ERR(SUS,EQN)
      IMPLICIT REAL *8(A-H,O-Z)
      COMMON/FFF/SH,NP
      COMMON/VEDATA/AM, BM, TK, SKNCT, CNCT, PI
      COMMON/PROFIL/U,AL
      DIMENSION EQN(2)
      COMMON/ROHH/ROH
      DIMENSION SUS(2), H(128)
      COMPLEX *16  SH(128), SHSH
C
      C = 34600.0
      SK = 500.0
      DO 222 ISK=1,400
      SK = ISK*500.0
C     WRITE(6,101)SH
  101 FORMAT('SH =',2D17.6)
C
      ALPH = 3.0
C     WRITE(6,402)AM,BM,TK,PI
  402 FORMAT('AMBM ETC ',4E15.6)
      DO 10 I=1,128
      SHSH = SH(I)
      HHH = SHSH*DCONJG(SHSH)/2.0
      HHH = DSQRT(HHH)
   10 H(I) = HHH
C     WRITE(6,411)SUS
  411 FORMAT('SK & C ',2D17.6)
C     SK = (SUS(1))
C     IF(SK.LT.1.0D2)SK = 100000.0
C     C = (SUS(2))
C     IF(C.LT.10.0D2)C = 10000.0
      . = DSQRT(SK/BM)
          . .../75.0

      . . . . .

      . . . = 0.
      . . . = .
      . . . .
      . . . .
      . . . .
      ALFA = 0.0
      . . . = 0.0
      . . . = 0.0
      . . . = 0.0
      . . . = 0.0
C
C
      DO 1 N = 1,NP
      HN = H(N)
      PRI = DFLOAT(N*N)*A*A
```

(Please Print - better copy unavailable. [illegible])

```
         PR1/(PHWO)
C
410      FORMAT('  PR2 =',D17.7)
         AX1 = SK*(1.-PR2)*(AM*PR1-(SK+TK))+SK*SK
         AX2 = AM*PR1 - TK + SK*PR2
         D1 = AX1*AX1+C*C*PR1*AX2*AX2
C
         D21 = RPR2 -1. + (PR1*AM/TK)*(1.-RPR2)-(SK/TK)
         D22 = RPR2 - (AM*WO*WO + SK)/TK
C
         D2 = D21*D21 + (PR1*C*C/(SK*SK))*D22*D22
         BX1 = (1.-PR2)*(TK+AM*PR1)+2.*SK*PR2
         BX2 = PR1*PR2*C*C
C
C        WRITE(6,403)PR2
403      FORMAT('PR2 =',E17.6)
C        WRITE(6,404)D1,D2
404      FORMAT('D1D2 =',2E17.6)
         RPR2 = 1./PR2
         AY1 = RPR2 -1. +(PR1*AM/TK)*(1.-RPR2) -(SK/TK)
         AY2 = RPR2 - (AM*WO*WO+SK)/TK
C
         BY1 = 1./TK
         BY2 = (PR1*C*C/(SK*SK))*((AY2/SK)+BY1)
C
         ANUM1 = TK*TK*(PR1*C*C+SK*SK)
C
         HN2 = HN*HN
         FPR1 = HN2/(D1*D1)
         FPR2 = HN2/(D2*D2)
         ROHN1 = ROHN1 - FPR1*(D1*SK*TK-ANUM1*(AX1*BX1+AX2*BX2))
         ALFA1 = ALFA1+FPR2*(AY1*BY1+AY2*BY2)
         ROHD = ROHD + HN2*ANUM1/D1
         ALFD = ALFD + HN2/D2
C
         ROHN2 = ROHN2+ FPR1*(D1*TK*TK-ANUM1*AX2*AX1)
         ALFA2 = ALFA2+ FPR2*AY2*AY2
C        WRITE(6,409)ROHN1,ROHN2,ALFA1,ALFA2
409      FORMAT('ROHN1 & 2 ',2D17.6/' ALFA1 &2',2D17.6)
         DMXK=DMXK+2.*(D1*SK*TK-ANUM1*(AX1*BX1+AX2*BX2))/(D1*D1)
         DMYK=DMYK-2.*(AY1*BY1+AY2*BY2)/(D2*D2)
         DMXC=DMXC+(2.*C*PR1/(D1*D1))*(D1*TK*TK-ANUM1*AX2*AX2)
         DMYC=DMYC+2.*C*PR1*AY2*AY2/(SK*SK)
1        CONTINUE
         WRITE(6,412)C,SK,DMXK,DMYK,DMXC,DMYC
412      FORMAT('CSKDMXKDMYKDMXCDMYC',6D18.6)
C
222      CONTINUE
C
C        COEFFICIENT OF EQUATIONS 28 AND 29
C
         DD1 = DSQRT(ROHD)
         DD2 = DSQRT(ALFD)
C
         WRITE(6,405)DD1,DD2
```

(Please Print - better copy unavailable. E.S.)

```
      405   FORMAT('COLCD2 ',2E17.6)
            WRITE(6,408)ALFA1,ALFA2
      408   FORMAT(' ALFA1 ALFA2 ',2D17.6)
            CR1 = RCHN1/DD1
            CR2 = RCHN2/DD1
            CA1 = ALFA1/DD2
            CA2 = (C*W*W/(SK*SK))*ALFA2/DD2
            WRITE(6,407)CR1,CR2,CA1,CA2
      407   FORMAT('  CR1 CR2 ',2D17.6/'   CA1 CA2 ',2D17.6)
      C
            RATI1 = ALPF/ROH
            WRITE(6,204)RATI1
      204   FORMAT('ROH=',D17.6)
            RATIO1=CR1/CA1
            RATIO2=CR2/CA2
            WRITE(6,202)RATIO1,RATIO2
      202   FORMAT('IN DQN',2E18.6)
      C
      203   FORMAT('ROH =',E17.6)
      21    EQN(1) = RCH*CR1 + ALPH*CA1
      22    EQN(2) = ROH*CR2 + ALPH*CA2
            RETURN
            END
OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
OPTIONS IN EFFECT*  NAME = ERR      , LINECNT =        57
STATISTICS*    SOURCE STATEMENTS =         97,PROGRAM SIZE =     4004
STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
C
C      *************FUN
      SUBROUTINE FUN(F)
      DIMENSION F(128)
      COMPLEX A(128),AF(128),CMPLX
       COMMON/FFF/A,NP
      COMMON/VEDATA/AM,BM,TK,SK,C,PI
      COMMON/PROFIL/V,AL
       DO 4 I=1,NP
      F(I) = 0.0
      ANP = FLOAT(NP)
      DO 5 J=1,NP
      NI = I*J
      JJ = NI/NP
      ANI = FLOAT(NI)
      TH = 2.0*PI*((ANI/ANP)-JJ)
      SS = SIN(TH)
      CC = COS(TH)
      AF(I) = AF(I) + A(J)*CMPLX(CC,SS)
    5  CONTINUE
      ARF=REAL(AF(I))
      AIF = AIMAG(AF(I))
      RATI =ARF/AIF
      IF(I.LE.64)GO TO 2
      AIF = -AIF
    2 F(I) = AIF*SQRT(1.0+RATI*RATI)
    4 CONTINUE
      RETURN
      END
*OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
*OPTIONS IN EFFECT*  NAME = FUN     , LINECNT =       57
*STATISTICS*    SOURCE STATEMENTS =        27,PROGRAM SIZE =      1904
*STATISTICS*  NO DIAGNOSTICS GENERATED
```

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AUTOMOTIVE SUSPENSION CONTROL.(U)
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```
          C
          C        SUBROUTINE ROUGH STARTS
0001                 SUBROUTINE ROUGH(N,H)
0002               DIMENSION H1(1024)
0003               COMPLEX H(N)
0004               REAL*4 FMT(1)/'*'/
0005               READ(5,FMT)(H1(I),I=1,N)
0006               S=0.0
0007               DO 2 I=1,N
0008      2        S=S+H1(I)
0009               HAV = S/FLOAT(N)
0010               DO 1 I=1,N
0011               H1(I) = H1(I)-HAV
0012               H1(I) = H1(I)*0.3043
0013      1        H(I) = CMPLX(H1(I),0.0)
          C        WRITE(5,101) (H(I),I=1,N)
0014    101        FORMAT(1H1////' TERRAIN ROUGHNESS INPUT :'/
                  22X,'***********************************'///
                  22X,'HEIGHTS W.R.T. A REFRENCE'///
                  2(3X,4F12.5/))
0015               RETURN
0016               END
 *OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
 *OPTIONS IN EFFECT*  NAME = ROUGH   , LINECNT =       57
 *STATISTICS*     SOURCE STATEMENTS =          16,PROGRAM SIZE =        4862
 *STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
      C
      C        SUBROUTINE PSDCAL
               SUBROUTINE PSDCAL(H,S,NP)
               COMPLEX H(NP)
               DIMENSION S(NP)
               COMMON/VEDATA/AM,BM,TK,SK,C,PI
               COMMON/PROFIL/V,AL
               OMEGA = 2.*PI*V/AL
               ETA = OMEGA*SQRT(BM/SK)
               DO 1 I=1,NP
            1  S(I) = H(I)*CONJG(H(I))/(2.*ETA)
               RETURN
               END
 *OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
 *OPTIONS IN EFFECT*  NAME = PSDCAL  , LINECNT =      57
 *STATISTICS*     SOURCE STATEMENTS =      11,PROGRAM SIZE =       548
 *STATISTICS*  NO DIAGNOSTICS GENERATED
```

TERMINAL SYSTEM FORTRAN G(41336)

```
C
C     SUBROUTINE FFT
      SUBROUTINE FFT(A,N,NB)
      COMPLEX A(NB),U,W,T,CMPLX
C     DIVIDING ALL ELEMENTS BY NB
      DO 1 J=1,NB
    1 A(J) = A(J)/NB
C     REORDERING THE SEQUENCE
      NBD2 = NB/2
      NBM1 = NB - 1
      J = 1
      DO 4 L = 1,NBM1
      IF(L.GE.J)GO TO 2
      T = A(J)
      A(J) = A(L)
      A(L) = T
    2 K=NBD2
C     WRITE(6,101)(A(I),I=1,6)
  101 FORMAT(3F15.6)
    3 IF(K.GE.J)GO TO 4
      J = J - K
      K = K/2
      GO TO 3
    4 J = J+K
C     COMPUTATION OF FFT
      PI = 3.14592653589793
      DO 6 M=1,N
      U = (1.0,0.0)
      ME = 2**M
      K = ME/2
      W = CMPLX(COS(PI/K), -SIN(PI/K))
      DO 6 J=1,K
      DO 5 L=J,NB,ME
      LPK = L+K
      T = A(LPK)*U
      A(LPK) = A(L) - T
C     WRITE(6,102)A(LPK)
  102 FORMAT(2F13.5)
    5 A(L) = A(L)+T
    6 U = U*W
      RETURN
      END
OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
OPTIONS IN EFFECT*  NAME = FFT    , LINECNT =       57
STATISTICS*     SOURCE STATEMENTS =        36,PROGRAM SIZE =       130
STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
C
C      SUBROUTINE HCAL(DX2A,DX2B,XA,H,NP)
       SUBROUTINE HCAL(DX2A,DX2B,XA,H,NP)
       COMPLEX H(NP),XA(NP),DX2A(NP),DX2B(NP)
       COMMON/VEDATA/AM,BM,TK,SK,C,PI
       C1 = AM/TK
       C2 = BM/TK
       DO 1 I = 1,NP
1      H(I) = XA(I) + C1*DX2A(I) + C2*DX2B(I)
       RETURN
       END
*OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
*OPTIONS IN EFFECT*  NAME = HCAL    , LINECNT =       57
*STATISTICS*    SOURCE STATEMENTS =        9,PROGRAM SIZE =       572
*STATISTICS*  NO DIAGNOSTICS GENERATED
```

```
 C        FUNCTION SUBPROGRAM FOR 4TH ORDER RUNGA-KUTTA METHOD
          FUNCTION RUNGE(N,Y,F,K,H)
          INTEGER RUNGE
          DIMENSION PHI(50),SAVEY(50),Y(N),F(N)
          DATA M/0/
          M = M + 1
          GO TO (1,2,3,4,5),M
 1        RUNGE=1
          RETURN
 2        DO 22 J=1,N
          SAVEY(J) = Y(J)
          PHI(J) = F(J)
 22       Y(J) = SAVEY(J) + .5*H*F(J)
          K = K + .5*H
          RUNGE =  1
          RETURN
 3        DO 33 J=1,N
          PHI(J) = PHI(J) + 2.*F(J)
 33       Y(J) = SAVEY(J)+.5*H*F(J)
          RUNGE=1
          RETURN
 4        DO 44 J=1,N
          PHI(J) = PHI(J)+2.*F(J)
 44       Y(J) = SAVEY(J) + H*F(J)
          K = K + 0.5*H
          RUNGE = 1
          RETURN
 5        DO 55 J=1,N
 55       Y(J) = SAVEY(J)+(PHI(J)+F(J))*H/6.
          M = 0
          RUNGE = 0
          RETURN
          END
*OPTIONS IN EFFECT*  ID,EBCDIC,SOURCE,NOLIST,NODECK,LOAD,NOMAP
*OPTIONS IN EFFECT*  NAME = RUNGE    , LINECNT =       57
*STATISTICS*     SOURCE STATEMENTS =          32,PROGRAM SIZE =       1416
*STATISTICS*  NO DIAGNOSTICS GENERATED

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Computer, Suspension, Simulation, Terrain, Model, Ride, Vehicles, Control, Spring, Damper, Ride Control, Adaptive Control, Random Vibrations, Power Spectral Density of Terrains, Airsprings, Hydropneumatic Springs

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report contains the software package for an adaptive optimal suspension control system relative to terrain random vibration disturbances. The proposed problem solution is shown to fall into two separate program categories: a) recognition of the terrain and parameter selection, by means of an on-board minicomputer or microprocessor, b) optimization of suspension parameters for arbitrary terrain configurations obtained from terrain statistics and executed on a centrally located stationary computer facility.

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The interface between the stationary computer facility and the on-board microprocessor is accomplished by means of a data bank prepared at the stationary facility and permanently stored in the memory of the on-board microprocessor. The suspension parameters are set by a servo-control unit on the vehicle which is activated by the microprocessor. The servo-control unit regulates the supply and release of air in the hydropneumatic suspension system, thereby increasing or decreasing the spring rate according to the optimal requirements. In a similar manner the damper orifice size is increased or diminished depending on the required effective damping parameter. If need arises, the vehicle can operate at fixed suspension parameters. The results of the investigation are shown in graph form.